CARDIVNSWC TR-82-94/30 The Assessment of Fuel Cell Power Plants for Surface Combatants

Carderock Division
Naval Surface Warfare Center

Bethesda, Maryland 20084-5000

CARDIVNSWC TR-82-94/30 September 1994

Machinery Research and Development Directorate
Technical Report

THE ASSESSMENT OF FUEL CELL POWER PLANTS FOR SURFACE COMBATANTS

FINAL REPORT

by
Ward Boughers
Philippe Goubalt
Marc Greenberg
Todd Heidenreich
Ray Kornbau
Owen Ritter
Robert E. Smith
Joseph Woerner

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NDW-DTNSRDC 5602/50 (REV 2-93)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)

2. REPORT DATE
Sep 30 1994

3. REPORT TYPE AND DATES COVERED
Research and Development

4. TITLE AND SUBTITLE

THE ASSESSMENT OF FUEL CELL POWER PLANTS FOR SURFACE COMBATANTS, FINAL REPORT

5. FUNDING NUMBERS

Work Unit 1-8200-444
Surface Ship Technology Block Program
PEO 602121N, Tasks
RH21E42 and RH21E45

6. AUTHOR(S)

Ward Boughers, Philippe Goubalt, Marc Greenberg, Todd Heindenreich, Ray Kornbau, Owen Ritter, Robert E. Smith, Joseph Woerner

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Code 824
Naval Surface Warfare Center
Carderock Division, Annapolis Detachment
3A Leggett Circle
Annapolis, MD 21402-5067

8. PERFORMING ORGANIZATION REPORT NUMBER

CARDIVNSWC-TR-82-94/30

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of the Navy
Office of Naval Research
Mr. James E. Gagorik, ONR 334
800 North Quincy Street
Arlington, VA 22217-566

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report describes the results of a study undertaken to determine the impact of fuel cell technology on the design and effectiveness of future naval surface combatants. The study involved the collection of data to characterize four different fuel cell technologies; proton exchange membrane, molten carbonate, phosphoric acid, and solid oxide fuel cells. This information was used to expand current computer models to develop specific fuel cell plants that met the power requirements for several applications on a nominal 5000 Lton destroyer and a nominal 200 Lton corvette. Each of the fuel cell technologies was incorporated into several applications aboard the destroyer and corvette. These applications included combinations of centralized and distributed ship services power, and propulsion power. In addition, the impact of fuel cell technology was determined for a ship service power backfit option aboard a DDG-51 class destroyer.

The results of the impact on the ship designs were analyzed and a military assessment was conducted to address such issues as the impact of fuel cells on mobility, survivability, affordability, and on the environment. The report identifies which aspects of the fuel cell technologies have the greatest impact upon combatant ship designs and their operating costs. Recommendations are given for future technology deelopment efforts required to make fuel cells suitable for naval service.

14. SUBJECT TERMS

Fuel Cells, Ship Service Power, Ship Propulsion

15. NUMBER OF PAGES
222

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Same as report

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ADMINISTRATIVE INFORMATION

This report is submitted in partial fulfillment of Task 3 of the Enabling Technologies Task RH21E45 of the Surface Ship Technology Block Program (SC1A/PEO602121N). The work described herein was sponsored by the Office of Naval Research (ONR 452R) and managed by the Naval Surface Warfare Center.

The work described in this report was performed, in large part, by the following participants:

Ward Boughers, Band, Lavis & Associates, Inc.
Philippe Goubault, Band, Lavis & Associates, Inc.
Marc Greenberg, CDNSWC 211
Todd Heidenreich, CDNSWC 243
Robert Smith, CDNSWC 824
Joe Woerner, CDNSWC 824.

Supervision was provided by:

Jeff Benson, CDNSWC 66X (Initial Project Manager)
Ray Kornbau, CDNSWC 825
Owen Ritter, CDNSWC 22 (Final Project Manager)
Dan Winegrad, CDNSWC 0113.

Technical direction and assistance was provided by:

Wayne Adamson, CDNSWC 824
Art Chaiken, ManTech
Dick Milligan, NAVSEA 05R2
Phil Sims, NAVSEA 05D1
Sidney Cox, CDNSWC 808.

All of the participants listed above have constituted the Navy's "Fuel Cell Working Group".

Sponsorship and technical oversight for the program has been provided by:

Jim Gagorik, ONR 452R
John Tobin, NAVSEA 03R1.

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DEFINITIONS OF ACRONYMS, SYMBOLS AND MISCELLANEOUS TERMS

AC	Alternating Current
ARPA	Advanced Research Project Agency
ASF	Ampere per Square Foot
ASSET	Advanced Surface Ship Evaluation Tool
Backfit	Power plant and associated auxiliaries replaced, remainder of ship untouched
Baseline	Reference ship
BCC	Basic Construction Cost
BOP	Balance of Plant
BTU	British Thermal Unit
C	Centigrade (Temperature Scale)
CER	Cost Estimating Relationship
CIC	Command Information Center
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CODOG	Combined Diesel or Gas Turbine
CPO	Chief Petty Officer
cu ft	Cubic Foot
cu ft/kW	Cubic Foot Per Kilowatt
dB	Decibel
dBA	Decibel, A Weighted Scale
DC	Direct Current
Density	Weight Over Volume
DFM	Diesel Fuel Marine
DG	Diesel Generator
DiSSP	Distributed Ship Service Power
DOE	Department of Energy
DRPP	Direct Replacement Propulsion Power
DRSSP	Direct Replacement Ship Service Power
ERC	Energy Research Corporation
F	Fahrenheit
FC	Fuel Cell
FCMC	Fuel Cell Manufacturing Corporation
FT	Foot
Gal	Gallon
GFM	Government Furnished Material
GT	Gas Turbine
HCL	Hydrochloric Acid
HP	Horsepower
HR	Hour
HVAC	Heating, Ventilation and Air Conditioning
ICR	Intercooled Recuperated
IFC	International Fuel Cell
IMHEX^{RTM}	Internally Manifolded Heat Exchanger
IPS	Integrated Power System
IR	Infrared
Khrs	Kilohours
KT	Knot
kW	Kilowatt
kWh	Kilowatt Hour
LB	Pound
LB/FT^3	Pound Per Cubic Foot

LB/kW	Pound Per Kilowatt
LB/kW-hr	Pound Per Kilowatt Hour
LB/S	Pound Per Second
LCC	Life-Cycle Cost
LNG	Liquid Natural Gas
LT	Long Ton
mA/sq cm	Milli Amp Per Square Centimeter
MC	Molten Carbonate
MCC	Major Category Codes
MCFC	Molten Carbonate Fuel Cell
MCP	Maximum Continuous Power
MCPC	M-C Power Corporation
MCPLXS	Manufacturing Complexities
mg/cm^2	Milligram Per Square Centimeter
mV	Millivolt
MW	Megawatt
MW/YR	Megawatt Per Year
NM	Nautical Mile
NMHC	Non-Methane Hydrocarbons
NO_x	Nitrogen Oxides
NPV	Net Present Value
O_2	Oxygen
O&S	Operating and Support
OSHA	Occupational Safety and Health Administration
PA	Phosphoric Acid
PAFC	Phosphoric Acid Fuel Cell
Parametric	Of or relating to various parameters or characteristics
PDSS	Propulsion Derived Ship Service
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
Planar	Refers to shape of individual fuel cell, flat type
PM	Permanent Magnet (Type of Electric Motor)
Power Density	Power Over Weight or Volume
PPM	Parts Per Million
psia	Pound Per Square Inch Absolute
RCS	Radar Cross Section
RDT&E	Research, Development, Test and Evaluation
Reformer	Device that reforms fuel into gaseous hydrogen and other elements
ROM	Rough Order of Magnitude
S	Sulfur
SBIR	Small Business Innovative Research
SbSSP	Standby Ship Service Power
SCF/LB	Standard Cubic Foot Per Pound
SCR	Selective Catalytic Reactor
SFC	Specific Fuel Consumption
Shift Converter	Device that promotes the shift (conversion) of CO to CO_2
SO	Solid Oxide
SO_2	Sulfur Dioxide
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxides
SS	Ship Service
Stack	Refers to fuel cells themselves apart from auxiliaries
SWBS	Ship Work Breakdown Structure
TBO	Time Between Overhauls
TMI	Technology Management Incorporated

UUV	Unmanned Underwater Vehicle
V	Volt
WSF	Watt Per Square Foot
YR	Year
ZnO	Zinc Oxide
$/kW	Dollars Per Kilowatt

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CHAPTER 1

EXECUTIVE SUMMARY

This report describes the principal findings of a study, performed under the Office of Naval Research (ONR), Enabling Technologies Project, which was undertaken to determine the impact of fuel cell technology on the design, cost and effectiveness of surface combatants.

The study was carried out in four distinct tasks integrated in a joint effort as shown in Figure 1-1.

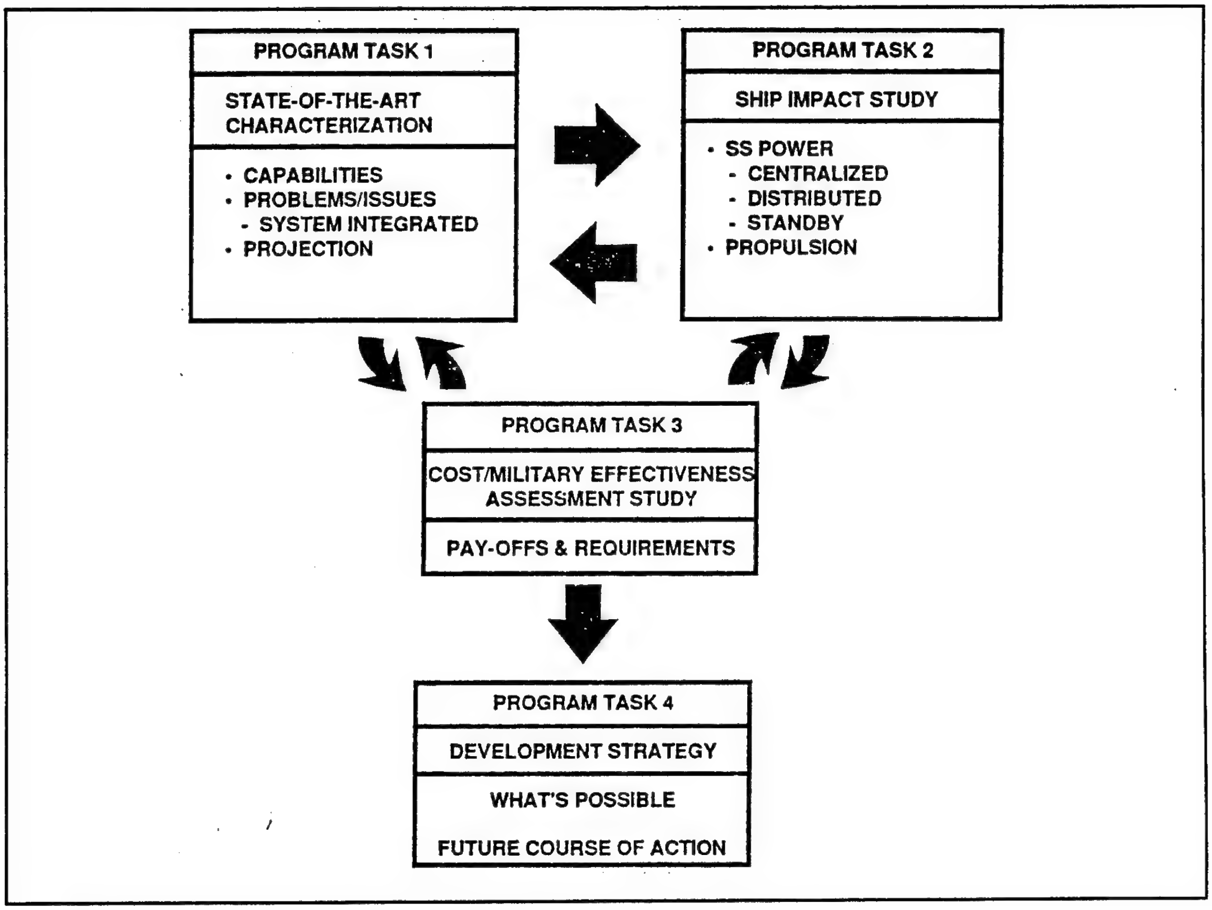

Figure 1-1. Task Integration Chart

Fuel Cell Technology Characterization

The first task consisted of characterizing the fuel cell technology in order to develop point designs of fuel cell plants for use in Navy ships. The study was limited to four major types of fuel cells listed below in approximate order of increasing operating temperature:

- Proton Exchange Membrane Fuel Cells (PEMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cells (MCFC)
- Solid Oxide Fuel Cells (SOFC).

The fuel cell plants examined in this study were required to operate on diesel fuel and air. Therefore, the point design plants included a diesel fuel reformer and a desulfurizer system as part of their components. Due to differences in the fuel cell designs, and the method used to process the diesel fuel, the various fuel cell types have different levels of compactness, efficiency, operating temperatures and sensitivities to their operating parameters.

Table 1-1 lists the efficiency and power density levels considered achievable for the various fuel cell types when they are designed for combatant service.

Table 1-1

Fuel Cell Power Systems Characteristic Summary

	Achievable for Combatants**			Land-Based Plant Sizes	
Fuel Cell Technology	% Eff	lb/kW	cu ft/kW	(1993)	(2010)
PEMFC	39-42	6.0-11.9	0.19-0.3	<120 kW	>1000 kW
SOFC (Planar)*	42-60	~8	0.29-0.38	R&D	MW Plants
SOFC (Tubular)	45-60	20-30	0.6-1.2	<100 kW	MW Plants
MCFC	40-55	40-60	0.98-2.1	<250 kW	MW Plants
PAFC	38-42	30-46	0.93-1.5	11 MW	Multi MW

*Planar SOFC data based on limited and projected data.
**For overall plant, fuel processing included.

Models of various types of fuel cells and reformers were developed and point designs of fuel cell plants were generated in various sizes ranging from 100 kW to 20 MW. All of the fuel cell types considered share three major attributes:

- A high efficiency
- Inherent covertness qualities (low signatures)
- Low level of pollution.

All three of these aspects were expected to yield great benefits for Navy combatant vessels.

Ship Impact Studies

The second task of the study was to conduct a ship impact assessment of fuel cells on combatant vessels. A baseline 2000 LT Corvette design, powered by a CODOG plant and a baseline 5000 LT Destroyer design, powered by an ICR electric-drive gas-turbine plant with permanent magnet motors, were developed using whole-ship design synthesis computer models.

Additional baselines (Corvette and Destroyer) using distributed (zonal) ship service power plants were also developed to provide a reference for distributed fuel cell plant configurations.

A DDG 51 baseline model was also established in order to assess a backfit variant using fuel cells for ship service power.

The information gathered as part of the fuel cell characterization task was used to expand the computer models to develop specific fuel cell plants that meet the power requirements for several applications on the ship considered.

The applications included combinations of centralized and distributed ship service power as well as propulsion power for both types of vessels and a backfit of the ship service power onboard a DDG 51 class destroyer.

In a first step, a parametric investigation of the impact of the weight-to-power ratio (lb/kW), density (lb/ft^3) and specific fuel consumption (lb/kW-hr) of a generic fuel cell on ship size, displacement, volume and power was conducted on a first order level.

The results, illustrated in Figure 1-2, showed that the fuel cell weight-to-power ratio was the largest driver of the ship characteristics listed above, while the specific fuel consumption would have a lesser influence. The fuel cell density was found to have only a second order effect on the fuel cell variants. Similar results were found for the Corvette and Destroyer, with a somewhat greater benefit for fuel cell variants for the Corvette due to the less advanced features of its baseline.

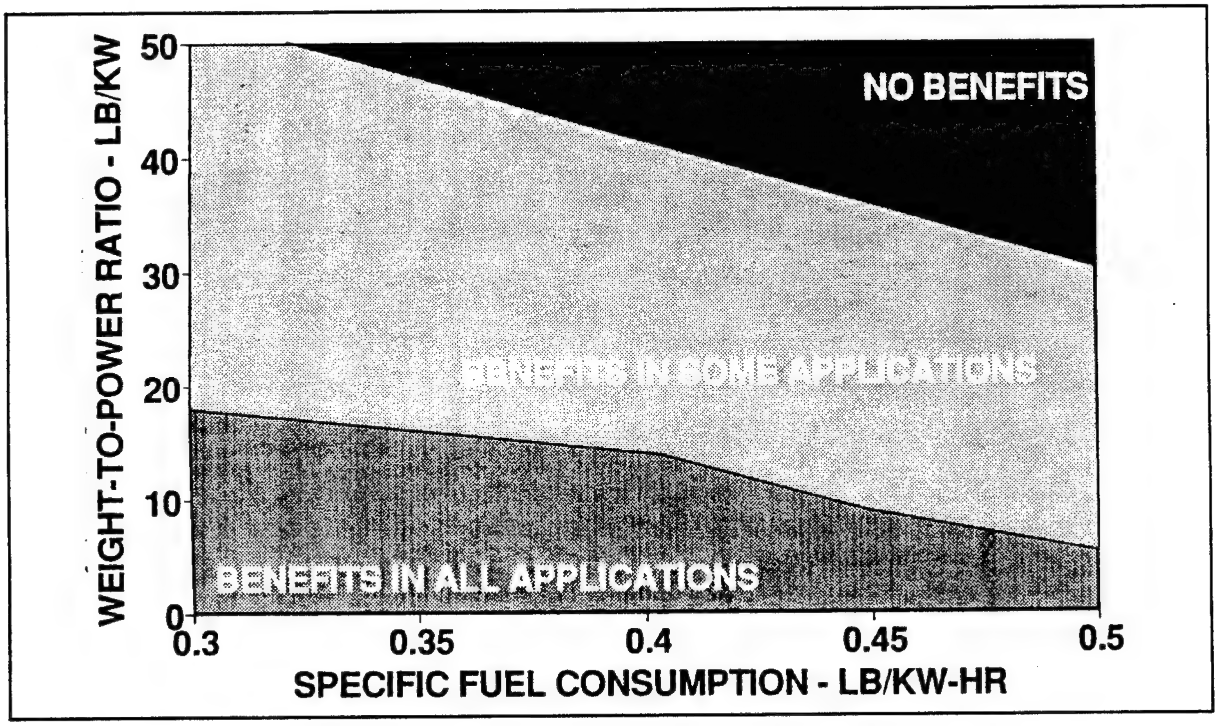

Figure 1-2. Influence of the Weight and Fuel Consumption of Propulsion Plants on Corvette to Destroyer Combatants

Following the parametric study, a more refined ship impact analysis was carried out by modeling more precisely the actual weight, space, auxiliary systems requirements and fuel consumption of each fuel cell type. Point designs were developed for each variant and each fuel cell type.

The results for the Corvette variants showed that significant reduction (relative to the baseline) in size, weight, volume, power and fuel consumption would result from PEM and SO fuel cells, with the most dramatic beneficial impact being with the propulsion variant as illustrated by Figure 1-3. The use of MC and PA fuel cells resulted in increased weight and volume and, subsequently, increased power requirements and fuel consumption in all applications, with the largest negative impact found in the propulsion variant.

Similarly, the Destroyer variants showed greater benefits (relative to the baseline) with the PEM fuel cells (SOFC point designs for the Destroyer were not produced) than with the MC and PA fuel cells. The most

significant impact was found in the volume required, especially, for intake and exhaust stacks, while the most dramatic overall impact (beneficial) was on the distributed PEM ship service variant.

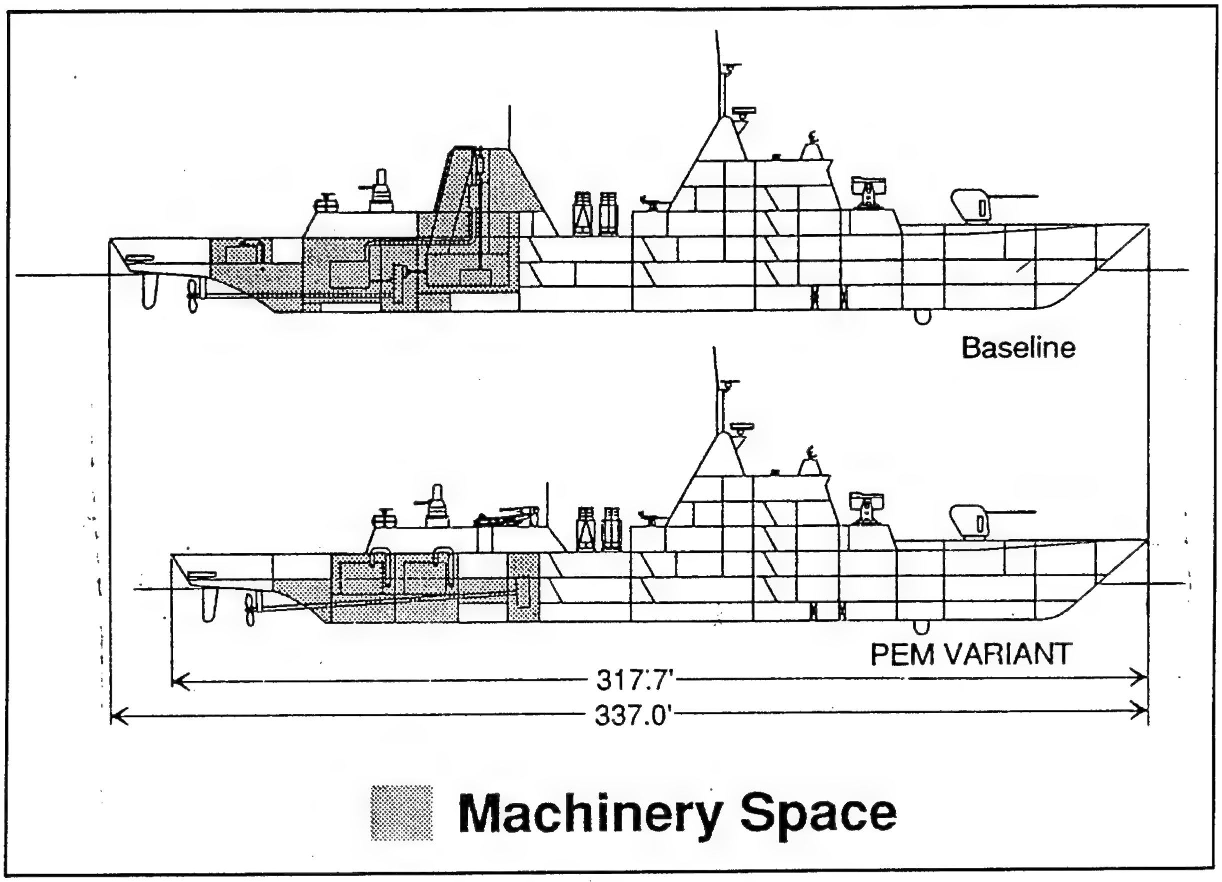

Figure 1-3. Propulsion Application, Corvette

The MC and PA fuel cell variants of the Destroyer showed significant increase of weight and volume (except for intake and exhaust stacks), with the largest negative impact being on the propulsion variants. However, fuel savings were still achieved by these fuel cell types compared to the baselines.

In the DDG 51 backfit variant, the use of PEM fuel cells had a significant positive impact on the electric plant weight and volume (exhaust stacks, in particular) and on the fuel efficiency and, therefore, on the range/endurance of the ship. Positive impact was seen for all the fuel cell types studied in this application.

Military Effectiveness and Cost Assessment

The third task involved an assessment of military effectiveness and cost.

The assessment of military effectiveness showed that outstanding benefits may be expected in the area of signatures, especially with regard to infrared signatures where fuel cell plants are expected to have an overall signature reduced by a factor of up to ten (relative to baseline). Figure 1-4 illustrates this aspect by showing the total heat rejected through the exhaust for the baseline Destroyer (using ICR gas turbines) and for the propulsion variants of all four fuel cell types. It should be mentioned that heat exchangers are inherent in the fuel cell plants and contribute to a reduction in the heat rejected to the atmosphere and an increase in that rejected to the sea. To accomplish similar results in conventional power plants would require increased weight and volume to accommodate the required heat exchangers.

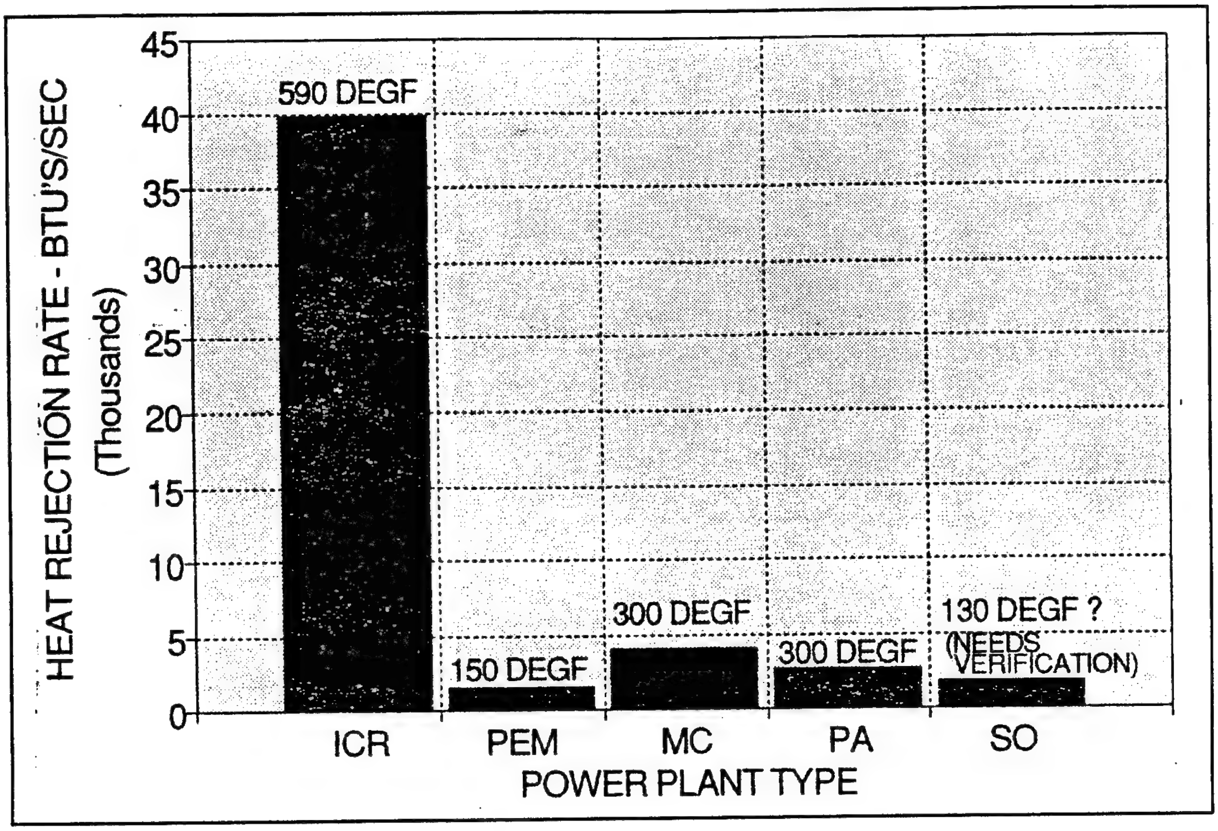

Figure 1-4. Heat Rejected to Atmosphere - Destroyer Operated at 28.1 Knots

Acoustic signatures are also expected to be significantly reduced since fuel cell stacks have no combustion or moving parts. Fuel cell acoustic characteristics are expected to be dictated by the principal auxiliaries (pumps, blowers) of the plant for which acoustic control techniques are already well developed.

Additional benefits are also found with regard to radar signature because of the reduction or elimination of exhaust stacks (see Figure 1-3, for example) which was made possible by reduced exhaust emissions and temperature.

Fuel cells are also expected to yield benefits regarding survivability as they are modular in nature and may be easily reconfigured or repaired after damage. However, the shock and vibration resistance of fuel cells has yet to be demonstrated.

Few benefits were found in this study regarding mobility because all designs were developed to meet the same operational requirements. However, the fuel savings resulted in reduced fuel load and/or increased range for the fuel cell variants. Start-up time and number of starting cycles were identified as specific issues where fuel cells will need to be improved as part of the development of marine fuel cell plants.

Some synergy was found with the use of future electric weapons as fuel cells produce electric (DC) power and are capable of absorbing overloads of up to two or three times their design load.

Although the environmental impact is not truly a military effectiveness issue, it was assessed as part of the overall effectiveness. It was found that fuel cells would allow significant reductions of the amount of pollutants rejected to the atmosphere as illustrated in Figure 1-5. This unique feature of fuel cells may become a major asset in a world where environmental issues are becoming increasingly important.

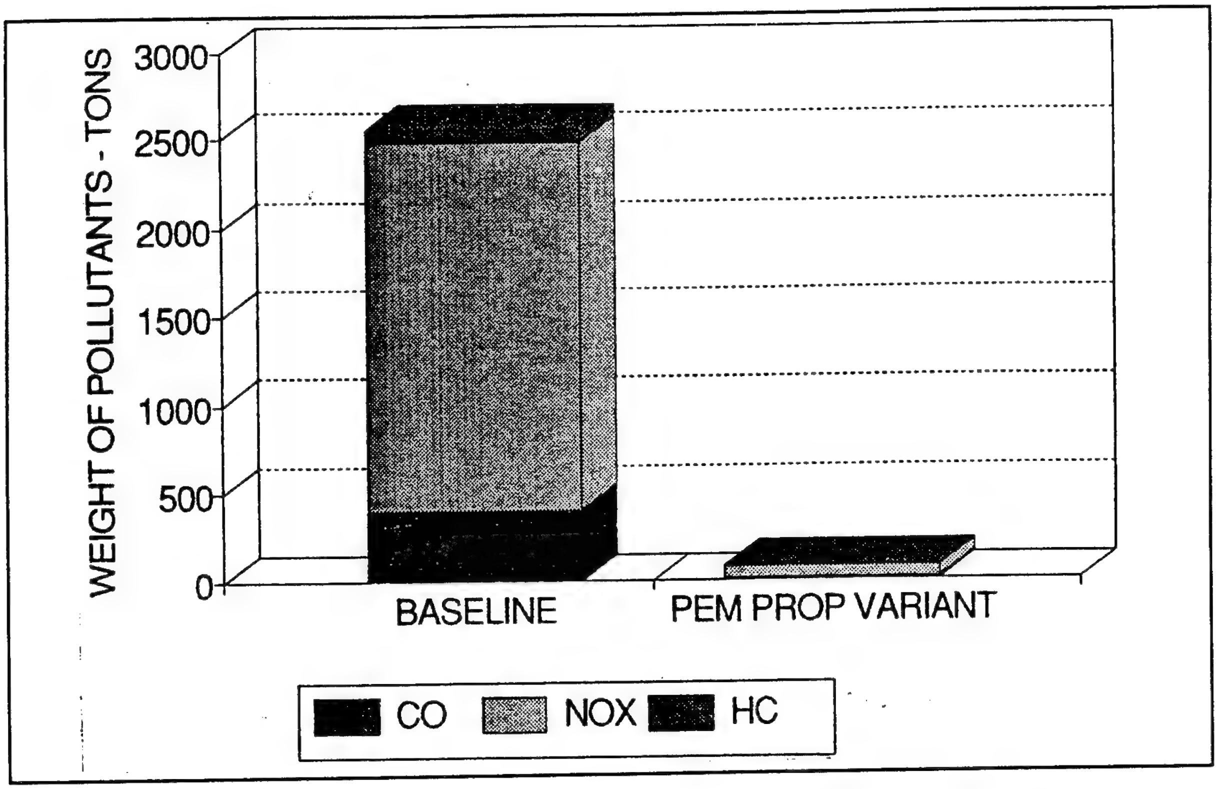

Figure 1-5. Pollutants Emitted to Atmosphere During Life of Corvette

A cost assessment of the baselines and the PEM fuel cell variants was carried out. The result of this study showed that, although all fuel cell variants were found to be more expensive than their respective baseline, the cost difference was small (less than 5%). This conclusion applied to ship end cost as well as life-cycle cost.

In addition, conservative assumptions were made regarding the maintenance requirements of fuel cell plants. A sensitivity analysis showed that the PEM variants could, under more optimistic assumptions, be less expensive by up to 5% than their baselines.

It was found that fuel savings in some variants were significant as illustrated by Figure 1-6. However, significant life-cycle cost savings were not gained as fuel does not represent a large proportion of the operating and support cost of a combatant vessel. This conclusion may not be the same for another type of vessel such as an auxiliary vessel or a sealift ship.

Another result of the cost study was that the largest cost driver for fuel cells lies in the balance of plant, comprising at least half the cost of a fuel cell system, rather than in the fuel cell stack itself.

The cost estimates did not account for the potential environmental and signature reduction measures that would be required on the baselines to satisfy the same standards in these fields as the fuel cell plants.

Development Strategy

A development strategy was established that would capitalize on two major considerations regarding fuel cells: their potential for dual use and their environmental characteristics.

The proposed strategy will focus on cooperation with other government agencies, the Navy and with industry. The promulgation of the results of this study among these concerns can help establish goals and

promote such cooperative efforts. The requirements of a high power density (low weight-to-power ratio, see Figure 1-2) fuel cell is common to all transportation vehicles and it is, therefore, envisioned that intermediate steps for the development of Navy-ship-capable fuel cells may parallel goals for truck and train power plants. A cooperation with DOE and other agencies is, therefore, envisioned to share the burden of developing fuel cell technology that would be applicable to land-based transportation as well as Navy ships.

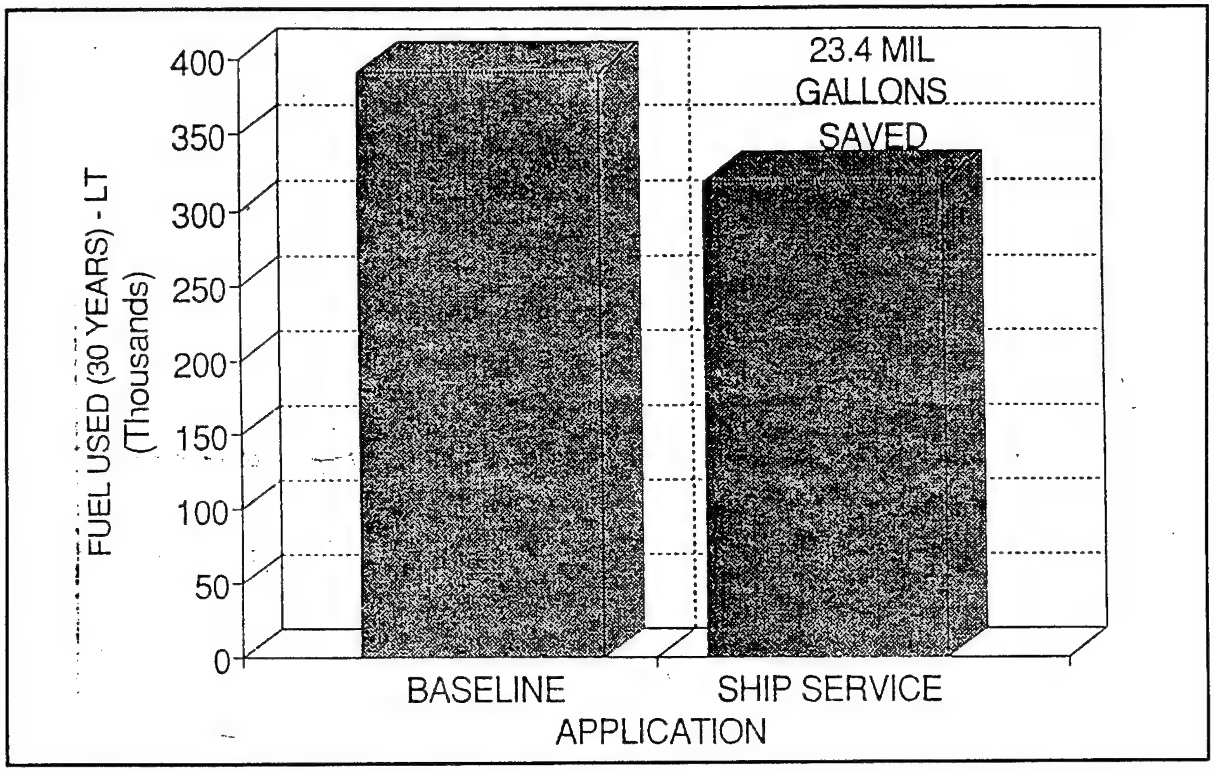

Figure 1-6. Fuel Consumed Over Life of Ship, Baseline and PEM Variant, DDG 51

Specific issues relative to the marine environment and/or Navy requirements will need to be addressed in the meantime through appropriate technology developments, but it is anticipated that prototype plant demonstrations will be achieved through the cooperation mentioned above.

A schedule for such a development was drafted that would yield production plants in the 2 to 3 MW range by the year 2004 and in the 10 to 20 MW range probably around the year 2020.

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CHAPTER 2

CHARACTERIZATION OF FUEL CELL TECHNOLOGY

2.1 Introduction

The fuel cell assessment program was organized into four major tasks. The first was to characterize the fuel cell types to be analyzed in order to supply data for the second task which would incorporate the technology into ship designs for analysis. The characterization effort was broken down into three major subtasks which were:

1. Define the general characteristics of the fuel cell types examined

2. Perform a survey of fuel cell plants that have been built (list of manufacturers included in Chapter 6).

3. Based on known or projected performance of the fuel cell type, produce point designs of fuel cell plants at various power levels to be used in the ship impact study.

The point designs of fuel cell plants form the basis for comparison with the baseline power plants. Details can be found in Table A-1 of Appendix A.

The point designs of the fuel cell plants used in this study are conceptual in nature. Fuel cell plants that operate on Diesel Fuel Marine (DFM) in the sizes used in this study have yet to be built and tested. However, most aspects of the technology have been demonstrated at the component level.

Design Requirements

The fuel cell power plants examined in this study are required to operate on diesel fuel and air. The point designs include fuel processors or reformers to convert the diesel fuel to a hydrogen rich gas suitable for use in a fuel cell.

A difficulty with using diesel fuel in fuel cell plants is the sulfur content. Fuel cells and fuel processors are highly intolerant of sulfur (which degrades performance) and require that sulfur be removed from the fuel down to a few parts per million. For the purposes of this study, it was assumed that the diesel fuel used would contain 0.5 % sulfur, even though it is expected that the majority of diesel fuel used by the Navy after the year 2000 will contain a maximum of 0.1 % sulfur. The Clean Air Act of 1991 currently limits the sulfur content of diesel fuel to 0.05% for over the road applications. The point designs include onboard sulfur removal systems, which adsorb sulfur in regenerable beds. The beds are periodically regenerated by the introduction of air to convert hydrogen sulfide to sulfur dioxide, which is then vented out with the exhaust. It should be noted that the technology exists today to provide sulfur free diesel fuel and that the sulfur content in commonly sold diesel fuel is being gradually reduced.

Fuel Cell Types

Four different types of fuel cells, classified according to the type of electrolyte used, were examined in this study. These fuel cells, listed in the order of increasing operating temperature, are:

- Proton Exchange Membrane (PEM)
- Phosphoric Acid (PA)
- Molten Carbonate (MC)
- Solid Oxide (SO), Planar and Tubular types.

Fuel Cell Definitions

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. In a typical fuel cell, gaseous fuels are fed continuously to the anode (negative electrode) compartment and an oxidant (i.e., oxygen from air) is fed continuously to the cathode (positive electrode) compartment; the electrochemical reactions take place at the electrodes to produce an electric current.

The typical electrode reactions that occur with different fuels and oxidants are summarized in Table 2-1. CO and CH_4 are sources of H_2 from water-gas shift reactions and steam-reforming reactions in the MCFC. Direct oxidation of CO and CH_4 is also accomplished in high temperature SOFCs.

Table 2-1

Typical Electrochemical Reactions In Fuel Cells

Fuel Cell	Anode Reaction	Cathode Reaction
Proton Exchange	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Molten Carbonate	$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{=} \rightarrow 2CO_2 + 2e^-$	$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{=}$
Solid Oxide	$H_2 + O^{=} \rightarrow H_2O + 2e^-$ $CO + O^{=} \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^{=} \rightarrow 2H_2O + CO_2 + 8e^-$	$O_2 + 4e^- \rightarrow 2O^{=}$

A fuel cell stack usually consists of a number of individual cells connected in electrical series to obtain the desired voltage. Cells can also be arranged in parallel to provide more capacity. In the case of PEM, PA and MC fuel cells, the individual cells are normally stacked in a planar manner, with a separator plate between each adjacent cell to separate the reactants. Solid oxide fuel cells may be planar also, however the most developed SOFC is the tubular type (planar and tubular refer to the cell shape).

A fuel cell power plant normally consists of the major components shown in Figure 2-1, i.e., a fuel processor, the fuel cell stacks and auxiliaries. Depending on the type of fuel cell and system design, potable water and useful heat may be by-products. Since the process is mostly electrochemical in nature, fuel cell exhaust is essentially non-polluting.

The auxiliaries required are normally referred to as the Balance of Plant (BOP). For a fuel cell operating on diesel fuel, the BOP includes a fuel processor to convert diesel fuel into hydrogen and CO, a shift converter to convert CO to CO_2 (if PEM or PA fuel cells are used), heat exchangers, condensers, controls and regulators. Additional equipment is included to remove sulfur from the diesel fuel.

Operating Parameters

The operating temperature of a fuel cell power plant is primarily fixed by the type of electrolyte used. Table 2-2 shows the normal operating temperatures. Fuel cell power plants can be designed to operate at various pressures and voltages. Increasing the operating pressure has the effect of increasing the available current at a given voltage and has benefits as long as the power required to pressurize does not

exceed the increase in performance. In general fuel cell power plants operate in the 1 to 8 atmosphere range.

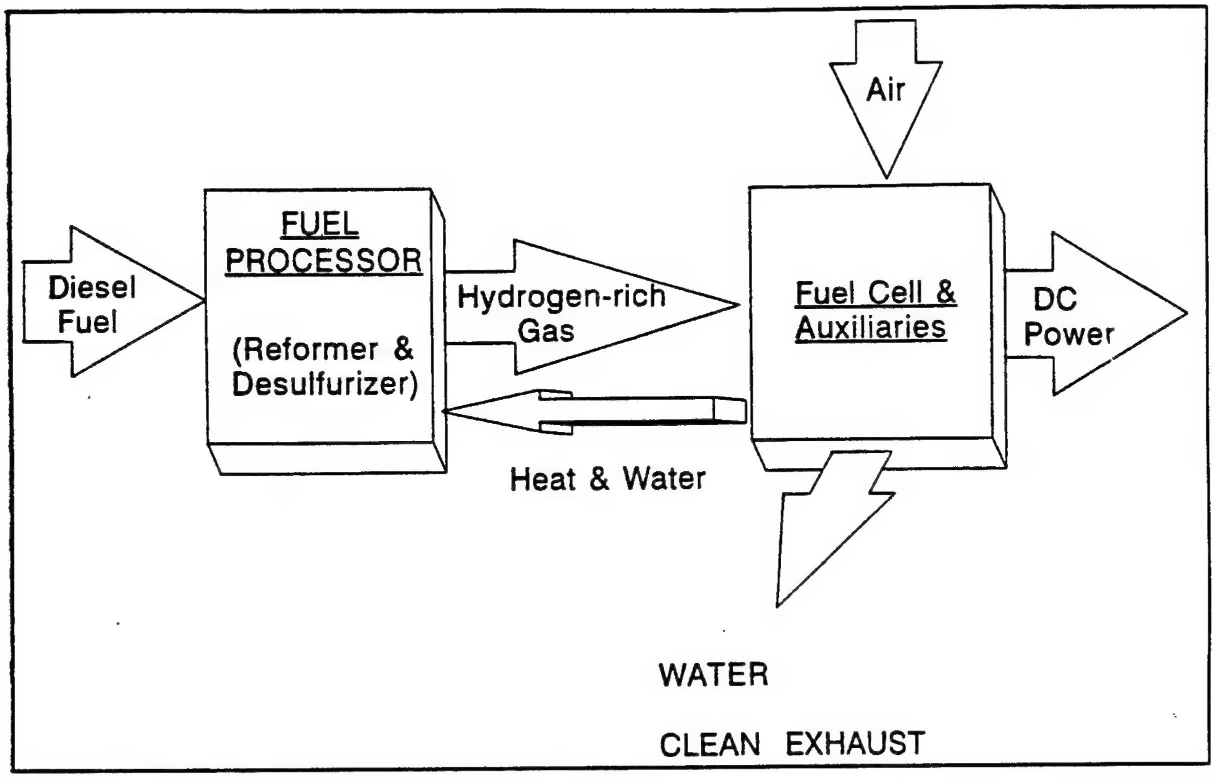


Figure 2-1. Schematic of the Basic Operating Parameters of a Fuel Cell Plant

Table 2-2

Operating Temperatures of Fuel Cell Plants

Type	Electrolyte	Operating Temperature (°F)
Proton Exchange Membrane	Sulfonated Polymer (Solid)	180-250
Phosphoric Acid	Phosphoric Acid (Liquid)	350-450
Molten Carbonate	Carbonate Salts (Liquid)	1200-1400
Solid Oxide	Zirconium Oxide (Solid)	1700-1900

As the operating voltage of a cell increases, the power plant efficiency generally increases as do the plant weight, volume and capital cost. Therefore an optimum design pressure and voltage exist for fuel cell applications onboard ships. These optimum design points were chosen for each type of fuel cell to produce a ship of optimum displacement, power and cost.

2.2 General Characteristics and Development Status

2.2.1 PEM Fuel Cells

Proton Exchange Membrane (PEM) fuel cells were first used in the late 1950s as the power source for Gemini spacecraft. These 1 kW powerplants operated at 34 A/ft^2 at 0.78 V on pure hydrogen and oxygen at 20-30 psia and 35° C. Life of the hydrocarbon-type polymer membrane was limited to <500 hours. Research in the late 1960s led to the development of Nafion (registered trademark of E.I. Du Pont de Nemours for perfluorcarbon sulfonate membrane), which is electrochemically stable up to 100° C. A new series of perfluorinated membranes, which hold the promise of higher temperature capability, became available from Dow Chemical Company in 1986.

The advantages of PEMFCs are:

- A high power density
- No free corrosive liquid in the cell.
- Simple to fabricate and operate.
- The membranes are capable of withstanding large pressure differentials.
- Operable at low temperature and relatively quick start up.

The disadvantages are:

- Water-management in the membrane is critical (fuel gas must be humidified)
- Carbon monoxide is an anode poison.
- The low operating temperature makes heat recovery unlikely and, therefore, limits the potential for improvement of efficiency.
- Sulfur intolerant.

Currently PEM fuel cells are being developed in the United States for automotive and naval applications. General Motors Corporation in cooperation with the Los Alamos National Laboratory is currently developing a methanol-fueled PEM fuel cell system for automotive applications. Fuel cell stacks are being provided by Ballard Power Systems, Inc. Ballard is conducting a program to develop a PEM fuel cell powered bus that runs on compressed hydrogen and delivered the initial bus in June 1993.

A 15 kW PEM power plant, using Nafion membranes, is being developed by International Fuel Cells (IFC) for the Advanced Research Project Agency (ARPA) high energy density unmanned underwater vehicle (UUV). Under this program a 20-cell stack was operated for 2175 hours at an average current density of 260 ASF with ±7 mV cell-to-cell variation. The 20-cell stack showed zero seal leakage after 2000 hrs of operation. A UUV power plant containing an 80-cell 7.5 kW stack was also tested at IFC.

A 10 kW PEM power plant, using Nafion membranes, and operating on diesel fuel and air is being demonstrated under the Navy's Surface Ship Technology program by Analytic Power Corporation. The emphasis of this program has been to achieve high power density and to reduce costs. Catalyst loadings have been reduced by an order of magnitude to <0.4 mg/cm^2 and power densities of 765 WSF have been demonstrated.

Siemens (Germany) has built and demonstrated in the laboratory several 34 kW PEM power plants. The Nafion membrane plant produces power from hydrogen and oxygen and has a 52 volt output and is intended for submarine service.

Table A-2 of Appendix A provides additional information on PEM technology status.

2.2.2 MC Fuel Cells

DOE is currently supporting MCFC development at two U.S. manufacturers, Energy Research Corporation (ERC) and Molten Carbonate Power,Inc. (M-C Power). Both of these manufacturers are nearing completion of the stack engineering phase and are involved in system demonstrations.

MCFC stack designs incorporate either internal or external manifolds. All MCFC stacks employ flat tape cast porous electrodes and matrices. Approximately 50-70 % of the stack weight results from the sheet metal manifolds, current collectors and separator plates. Current state of the art performance is 0.7 to 0.75 V at 120 A/ft^2 at atmospheric pressure.

The advantages of MCFC are:

- High thermal efficiency (>50 % on natural gas)
- CO is a fuel
- The 1200°F operating temperature allows internal reforming of gaseous fuels.
- Approximately 80 % of the MC stack is recyclable
- Heat recovery is possible (using a bottoming cycle) thus improving potential for high efficiency.

The disadvantages are:

- Relatively low power density
- CO_2 must be recycled from the anode exhaust to the cathode inlet.
- Electrolyte leakage and migration (essentially eliminated in the internally manifolded design).
- Sulfur intolerant.
- Chlorides react with the electrolyte and can cause failure due to electrolyte evaporation. (limit for HCL is 1 ppm).
- Long start-up time requiring an external energy source.
- Good high temperature insulation required to limit transfer of heat to ship.

Other details of Molten Carbonate fuel cell technology are summarized in Table A-3 of Appendix A.

MCFC Status at Energy Research Corporation

ERC through its manufacturing subsidiary, Fuel Cell Manufacturing Corporation (FCMC), operates a stack production facility rated at 2-5 MW/yr. At present 6 square foot area cells are manufactured and assembled into stacks up to 250 cells. Previously several 4 square foot area stacks were built and tested. ERC has recently completed the design of a 2 MW natural gas fueled system to be demonstrated in Santa Clara, CA. during 1995-1996. The power plant will consist of 16 stacks each rated at 125 kW. The initial 125 kW stack achieved greater than 50% overall efficiency on natural gas.

ERC stacks designed to operate on natural gas, employ internal reforming plates in which the heat for the exothermic reforming reaction is provided directly by the waste heat of the stack. Typically there is one reformer plate for every 6 cells. Under a NAVSEA SBIR, operation of a small 700 watt MCFC plant on a liquid fuel, EXSOL D110 (sulfur-free fuel) was demonstrated. The liquid fuel and steam were converted to a methane rich gas external to the stack, and then further reformed in the stack.

A total of 600 hours of operation with Exsol D110 was accomplished with no degradation of stack performance.

MCFC Status at M-C Power Corporation

M-C Power Corporation was formed in 1987 for the sole purpose of commercializing MC fuel cells using the internally manifolded heat exchanger (IMHEX ^{RTM}) stack design concept. The Institute of Gas Technology, which invented the IMHEX concept provides the fundamental technology. Scale-up and development has been the focus including the successful operation of several 20 kW stacks that runs on natural gas. Current focus is in the design and demonstration of 250 kW process development power plants in 1994-1995. Prototype plants in the several MW class are planned for the 1996-98 time frame.

2.2.3 PA Fuel Cells

PA fuel cell technology was the first to be developed for commercial applications, and is being demonstrated by both United States and foreign manufacturers, identified in Table A-4 of Appendix A. An 11 MW water-cooled PAFC plant, built by IFC utilizing 700 kW stacks, began operation in 1991. IFC also has a semi-automated production facility for PAFC plants up to 1 MW and is currently producing 200 kW natural gas fueled power plants. As of July 1993, 56 plants were delivered and these plants have accumulated over 100,000 hours of operation, with an operational availability in the field of >90%. The 200 kW plants, which operate at atmospheric pressure are designed to produce 0.665 V per cell at 200 A/ft^2.

The advantages of PAFCs are:

- In production
- Multiple manufacturers
- Low operating temperature
- Tolerant to CO up to 4%.

The disadvantages of PAFCs are:

- Corrosive electrolyte
- Long term life of plants not demonstrated
- Sulfur intolerant.

PAFC stacks are characterized by methods of stack cooling, operating pressure, and electrolyte management techniques. Stacks may be water or air cooled. Air-cooled plants have been demonstrated by Westinghouse up to 4.8 Atmospheres; this technology is now being further developed by the U.S. Fuel Cell Corporation. Since some electrolyte is lost during operations, the designer has the option of letting the cell components hold sufficient electrolyte for the desired life, or electrolyte may be added periodically. Both approaches have been used.

Development goals for advanced water-cooled PAFC stacks operating at 8.2 Atmospheres are 0.75 V/cell at 400 A/ft^2. In the air cooled version, which operates at 4.8 Atmospheres the design goal is about 0.7 V/cell at 250 A/ft^2.

Cost and life of PAFC systems remain as issues. Manufacturing and design changes are being introduced which are expected to significantly reduce cost. While the design life of PAFC systems is 40,000 hours, the longest reported stack test is less than 20,000 hours. Long term stack endurance tests are required.

2.2.4 SO Fuel Cells

SOFCs like MCFCs accept both hydrogen and carbon monoxide as feed to the anode. SOFCs that utilize Yttria-stabilized zirconia electrolyte operate at about 1830° F and are unique in that oxygen atoms are ionized at the cathode, and are conducted through the electrolyte to the anode. At the anode-electrolyte

interface the oxygen ions react exothermically with the fuel to form water and carbon dioxide, while liberating electrons.

SOFCs present the following advantages over other fuel cells:

- Planar type show potential for highest power density and efficiency of types studied.
- CO_2 recycling is not required as in the MCFC.
- Less sensitivity to contaminants because of the non-liquid electrolyte and the high operating temperature.
- The high operating temperature allows internal reforming of gaseous fuel.
- High operating temperature provides waste heat that can be utilized for additional power produced through bottoming cycles.
- Electrolyte management is not a problem (no water or liquids).
- SOFCs can be fabricated in thin layers and require no excess electrolyte.

The disadvantages are:

- Ceramic material (brittle)
- Thermal stress from high operating temperature limits active area size
- Long start-up times
- The high operating temperature (1830 degrees Fahrenheit) is also a disadvantage, in that an external start up system is required to heat the fuel cell stack to operating temperature and good insulation is required to limit heat transfer to ship.

Status

Two basic types of SOFCs are under development. Westinghouse has developed a tubular design and built plants operating on natural gas. In the tubular design, cell construction consists of an anode, electrolyte, cathode and interconnection, configured as thin layers on a porous support or self-supported. Air feed tubes, power contacts, diffusion barriers, air an fuel plenums, and an internal combustion chamber are added to form a module of cells. Allied Signal, Ceramatec, ZTEK Corporation, and Technology Management, Inc. are developing planar designs. In the planar designs, thin flat cells and separator plates are stacked to form a module. A unique feature of the Technology Management, Inc. design is that the fuel electrode is separate from the cathode and electrolyte, providing design and material flexibility.

Westinghouse has field tested 3 nominal 25 kW SOFC plants, and is currently fabricating a 100 kW plant with improved design and long tubular cells for demonstration in a utility application in 1996. MW level demonstrations are projected in the 1997-98 time frame. The planar designs are currently in the research stage of development, but show the potential for achieving both high power density and high efficiency. At least two small (<100 W) planar SOFC stacks are expected to be operating within a year.

More detailed characteristics of SOFCs are summarized in Table A-5 of Appendix A.

2.3 Point Designs

2.3.1 Modeling Approach

Visits were made to various fuel cell contractors and literature searches made to obtain information on the various technologies.

2.3.1.1 PEM, MC and PA Types

PEM, MC and PA power plant performance was predicted using Computer Design Codes, developed by Analytic Power for the Navy. The programs, which assume operation on diesel fuel containing 0.5% sulfur, require the following input data:

- Net power required, kW
- Mechanical efficiency, percent (pumps, blowers, etc.)
- System pressure, Atm
- Cell voltage (affects efficiency and current density)
- Cell inlet temperature, deg F
- Hydrogen utilization, percent
- Water to carbon ratio in reformer (affects reformer efficiency).

Average cell performance is predicted from the input conditions applied and polarization curve data of the system involved. The polarization curves vary greatly with fuel cell technology. Then the stack performance is computed and compared with the required net power. If the comparison is not within design parameters, adjustments to the number of cells or cells per stack are made, and the process reiterated.

When the stack design meets the required parameters the program begins determination of the overall material balance. To obtain the necessary balance the size and performance of the fuel processing equipment is modified. When a balance is obtained, an energy balance is attempted. To attain a correct balance the gross power is modified and the cell and stack design is reiterated. These processes continue until both the material and energy balances are obtained. At this point, the following outputs are available:

- Net power output
- Exhaust temperature
- Exhaust flow rate
- Exhaust composition
- Air flow rate
- Seawater flow rate

The program then calculates the following cost data:

- Stack cost
- Balance of plant cost
- Life-cycle cost

Finally, the program calculates component and system weight and volume. A table of weight factors and material densities are used in conjunction with standard practices with regard to pressure vessel and heat exchanger design to establish the final weight data. The following data is generated:

- Weight and volume of;
  - Stack
  - BOP,
    - Reformer
    - Shift converter
    - Desulfurization equipment
    - Heat exchangers
    - Condensers

The design codes assume the system configurations shown in Table 2-3.

The following should be kept in mind, when reviewing the point design results. First, no fuel cell has operated on diesel fuel to data, although the PA, SO and MC types have been operated on lighter liquid

hydrocarbons. Second, it should be noted that only the PEM type was modeled using the more compact autothermal reformer, since the Navy did not have an ATR model for the other technologies. Use of an ATR with the other technologies would reduce the balance of plant weight and volume by an estimated 20 to 25%. Under an ARPA program, initiated in July 1994, an ATR for use with a 100 kW PA plant is being designed, fabricated and tested.

Table 2-3

Fuel Cell System Configurations

Fuel Cell Type	Reformer Type	Sulfur Removal Method	Operating Pressure (Atm)
PEM	Autothermal	ZnO Beds	6
MC	Steam	Hydrodesulfurizer and ZnO Beds	6
PA	Steam	Hydrodesulfurizer and ZnO Beds	8

2.3.1.2 SO Systems

No design code for solid oxide fuel cells was available to the Navy. Therefore, only published data or data provided by SOFC contractors are used in this study. As a result, the level of confidence of the solid oxide fuel cell data is not as high as that of the other fuel cell types. Also, the data used were for fuel cells operating at 1 atm. Thus, there is potential for improvement.

2.3.2 PEM Model Output

In Tables A-6 through A-9 of Appendix A, the PEM model output is shown for the approximate power plant sizes required for the ship impact study. Table A-8 is condensed and reproduced here as Table 2-4. The power plant characteristic data shown in Table 2-4 includes intake, exhaust, cooling, weight, size, fuel consumption and cost data. Potable water output is also shown.

In all PEM power plants an operating pressure of 6 atmospheres was used. A turbo compressor, which runs off of exhaust gases and unspent fuel was utilized to supply pressurized air.

A cell operating voltage of 0.75 volts at full power was chosen for use in the ship impact study, since that design point yielded optimum ship characteristics.

2.3.3 MC Model Output

Tables A-10 through A-13 of Appendix A show the model output for the approximate MC power plant sizes required for the ship impact study. These point designs are based on 10 sq. ft. area cells with internal manifolding. An operating pressure of 6 atmospheres, and a cell voltage of 0.65 volts were selected, since that point yielded optimum combatant ship characteristics.

ERC provided the data shown in Table 2-5 for their MC fuel cell utility stacks and a future Navy stack.

Dimensions of the future Navy stack are: length = 57 inches, width = 57 inches, height = 112 inches, which corresponds to a stack volume of 210 cu ft. ERC computer models estimate the full-load diesel fuel consumption rate as 0.35 lb/kWh.

Table 2-4

PEM Technology Fuel Cell Systems - Destroyer Propulsion Fuel Cell System

Nominal Power, MWatt	18.00		
Cell Design Voltage	0.70	0.75	0.80
Net Power, kWatts	18087.59	18087.57	18087.49
Air Flow, scfs	572.52	534.35	500.95
Exhaust Flow, scfs	597.93	558.07	523.46
Exhaust Temp, Deg F	150.00	150.00	150.00
Sea H2O, gpm	2990.25	2790.89	2616.43
Potable H2O, gpm	17.28	16.13	15.12
Cost: Fuel Cell, $/kW	265.16	312.33	387.83
Cost: BOP, $/kW	309.81	314.42	326.74
Fuel Cell Weight, LT	14.24	16.80	20.89
BOP Weight, LT	21.67	20.15	19.28
Desulfurizer Weight, LT	8.24	7.69	7.30
Fuel Cell Volume, cu ft	1518.87	1791.41	2227.45
BOP Volume, cu ft	1111.38	1047.93	1003.66
Desulfurizer Volume, cu ft	378.49	353.26	335.23
SFC, 125%, lb/kW-hr	0.4804	0.4631	0.446
SFC, 100%, lb/kW-hr	0.4633	0.4507	0.4377
SFC, 75%, lb/kW-hr	0.4509	0.4418	0.4321
SFC, 50%, lb/kW-hr	0.4451	0.4388	0.4316
SFC, 25%, lb/kW-hr	0.4585	0.4542	0.4491

Table 2-5

Direct Reforming Molten Carbonate Stack Weights

	Utility		Naval Future
	Present	Future	
Stack Design			
Cell Size, sq ft	6	6	10
Number of Cells	146	300	300
Power/Stack, kW	200	250	425
Weight			
Repeating Cell Component	8510[1]	6585	9880
Non-Repeating Components	3830[2]	2490	3490
Total, lb	12,340	9075	13,370
Lb/kW	61.7	36.3	31.5

(1) 246 cells and 41 reforming plates.

(2) End plates, manifolds, manifold compressors, insulation, cold compression plates, load bars, tie rods, belleville springs, other.

It is noted that the data shown in Table 2-5 assumes operation at 1 atm pressure and does not include the weight, volume, and inefficiencies of fuel cell auxiliaries of diesel fuel desulfurization equipment.

2.3.4 PA Model Output

In Tables A-14 through A-17 of Appendix A, the PA model outputs are shown. A design operating pressure of 8 atmospheres and a cell voltage of 0.7 volts were chosen since these points yielded optimum ship characteristics. The power density of PAFCs are between those of PEM and MC.

2.3.5 SO Data

No published data exists for SOFC plants operating on diesel fuel. Table A-18 of Appendix A lists the estimated characteristics of a Westinghouse tubular SO power plant designed for a natural gas fueled utility application. The power plant consists of 56 fuel cell modules, each containing 5004 cells, which are 150 cm in length. The plant has a rated DC output of 21.6 MW, but is capable of producing a peak power continuously at 44.3 MW. Corresponding thermal efficiencies are 50.5% and 39.5%.

Table A-20 of Appendix A lists projected characteristics of a natural gas fueled tubular SO plant, which has a gas turbine system as a bottoming cycle. The SO plant operation is at atmospheric pressure and is not fully integrated with the gas turbine. Subsequent analytical studies performed at Westinghouse indicate that SOFC performance will be enhanced by SOFC pressurization, and that pressurization will also enable more direct integration with the gas turbine. Both effects are estimated to improve overall power plant performance. Integration of the SO fuel cell with turbomachinery will enable coverage of the required operating range, according to Westinghouse. Additional analyses are warranted to quantify the efficiency gain achievable with a bottoming cycle.

Table A-20 of Appendix A contains preliminary estimates of the characteristics of planar SOFC plants. This data was provided by Allied Signal and Technology Management Incorporated (TMI). For the TMI plant, which uses a proprietary design approach, it is assumed that the SOFC will be sulfur tolerant, so that sulfur removal is not necessary. Again the use of a combined cycle is attractive from a system efficiency viewpoint.

TMI SOFC plant performance data was used in the ship impact study as it was readily available and the plants required no modifications to make them sulfur tolerant. No verification of their performance predictions was undertaken as part of this study and thus results in which the data are used are typically caveated with a question mark.

2.3.6 Comparison of Fuel Cell Types

Figure 2-2 compares the projected weight and volume of the fuel cell types studied. The comparison includes the fuel processor, the fuel cell stacks and all supporting auxiliaries. Sulfur removal equipment is included for all power plants except the planar Solid Oxide, since it is projected that the TMI planar SO plant can be made sulfur tolerant. A packing factor of 1.5 has been applied to all machinery-space calculations. In terms of weight and volume, the MC plants were the largest, while PEM and planar solid oxide were found to be the smallest.

In all cases except the SO power plants (no data available), the operating pressure was selected to achieve high power density. Trade offs were made to determine the effect of cell operating voltage on power plant weight and volume. This effect can be seen by examining the tables in Appendix A. In the case of the MC fuel cell, performance is greatly increased by elevating the pressure. However, to achieve a reasonable power density, the MC power plants had to operate at 0.65 volts per cell. This has the effect of reducing the MC power plant thermal efficiency. For applications where power density is less important, such as a transport ship, the MC efficiency could be increased at the expense of power density.

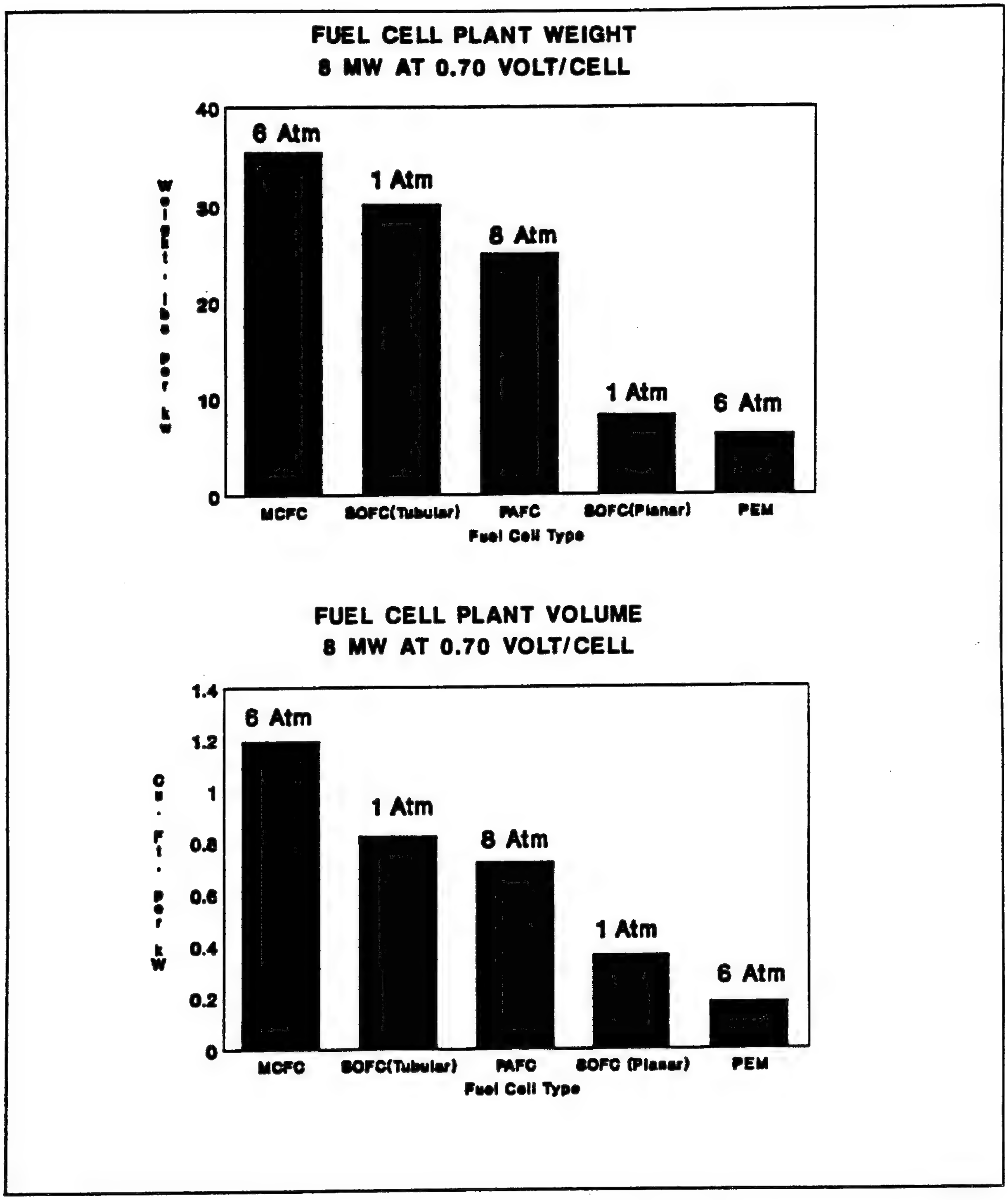


Figure 2-2. Fuel Cell Plant Weight and Volume

Although, only briefly examined, there appears to be merit in combining the high temperature fuel cell plants (MC and SO types) with a gas turbine. This allows recovery of the fuel cell waste heat in the turbine, resulting in overall thermal efficiency in the 60-70 % range.

2.4 Environmental Issues

Fuel cell systems are inherently non-polluting. The principal pollutants, e.g., NOX, HC and CO are eliminated in the fuel cells or in the fuel processing. Little, if any, unburned non-methane hydrocarbons are released due to the final catalytic burner feeding the air turbocharger.

The amount of CO_2 and SO_2 rejected by the fuel cell plants will be dependent essentially on the fuel consumption and the fuels used. The remaining sulfur could be removed altogether instead of being burned and fuel low in carbon would ultimately improve the simplicity and efficiency of the fuel cell plants by reducing the requirements for a fuel reformer. Therefore, fuel cell technology is poised for the future role of a completely **"green"** power system.

Future Requirements

Figure 2-3 illustrates the severity of proposed air pollution controls based on the California Air Resources Board (CARB) recommendations. The data, in grams per mile, is not directly applicable to marine vessels, however, the data is used here to point out the great advantage fuel cell technology has over all other means of energy conversion in meeting future emission standards, whatever they are.

NOx Emission

Fuel cells produce very little NOx. Figure B-1 of Appendix B shows the relationship of existing power system exhaust NOx concentrations and the CARB proposed levels. No effort at all is required for fuel cells to meet these standards. Diesel and gas turbine engines, on the other hand, will require a great deal of effort. For example:

> One method is to inject water into the combustion chambers of gas turbines. The DDG51 with four LM2500s would require a distilling plant capable of producing 130,000 gallons of water per day and factoring in the power required to operate it from the ship's power generation system makes it undesirable.
>
> Secondly, NOx may be removed from the tail gas in a selective catalytic reactor (SCR). This requires an ammonia system. About one pound of ammonia is required per pound of NOx removed, at $200 per ton, approximately. The impact of this method of NOx removal on system weight and cost is very large and can be seen in Figure B-2 of Appendix B.
>
> The most practical method of NOx control on future engines seem to be the use of special dry combustors. Manufacturers claim to have demonstrated a combustor having a 25 ppm NOx emission which fulfills the minimum requirement of 42 ppm in Figure B-1, and they optimistically look forward to a design for a 9 ppm combustor in the future. All of these require intensive development at unspecified costs. No additional cost, in this regard, is required for fuel cells.

SOx Emission

SOx emission at the present is a function of the sulfur content in the fuel. While little effort is being applied in preventing SOx emission by tail gas clean up, in the future it will almost certainly be necessary to greatly limit SOx emission and fuel cell technology can help achieve such goals.

Fuel cells are sulfur intolerant and all traces of sulfur must be removed from the fuel cell gas streams (with the possible exception of SOFC systems). To accomplish this task a system of metallic oxide adsorber beds are included in the design of each plant discussed in this report. The system consists of two adsorbers, one actively removing sulfur while the other is being regenerated with bleed air from the reformer inlet (Figure A-21 of Appendix A illustrates this process). At a prearranged time the units are

switched and the process continues uninterrupted. The system is sized to allow one year operation before bed replacement. A third smaller unit acts as a polisher removing all traces of sulfur.

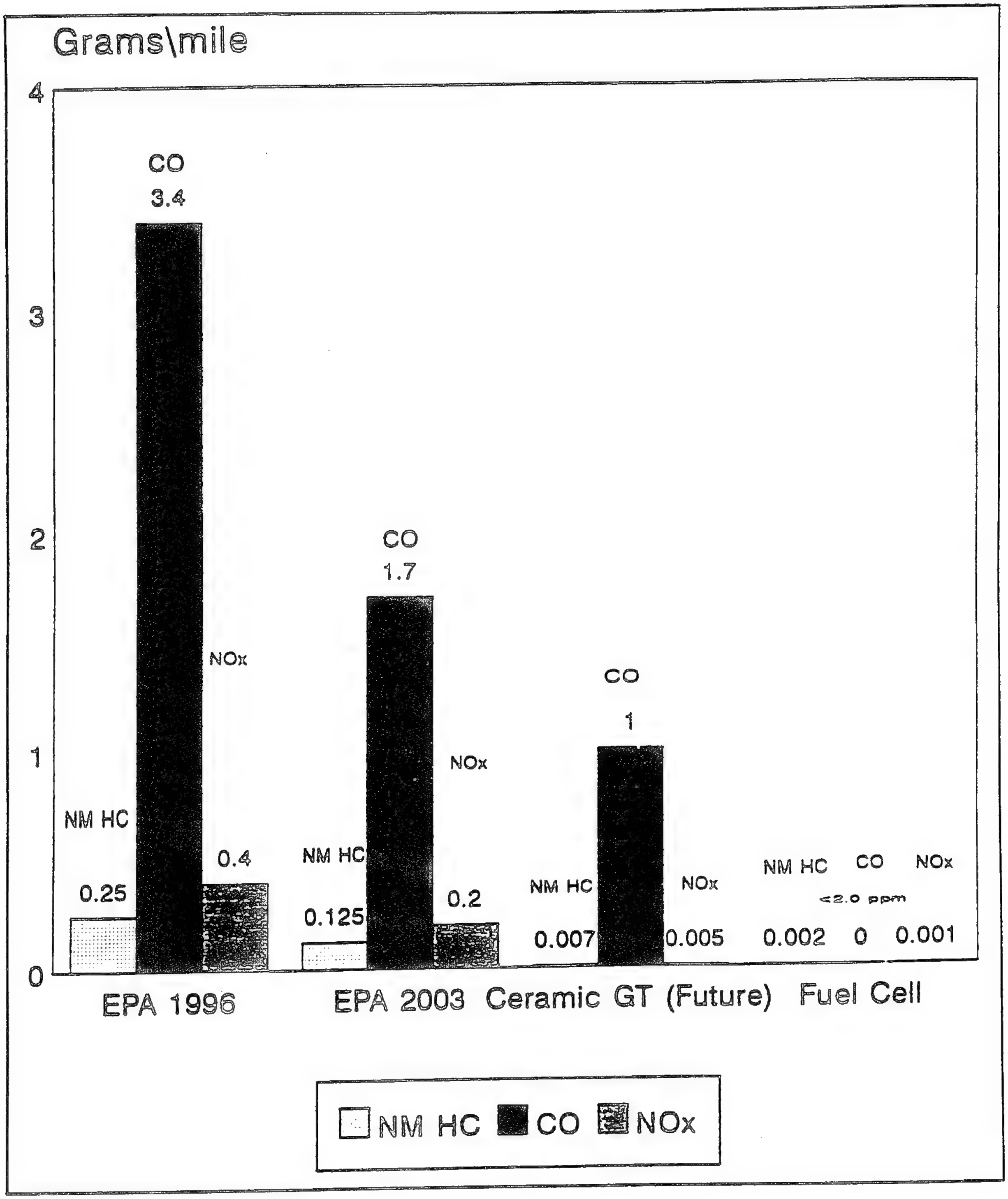


Figure 2-3. Proposed Environmental Standards for Transportation
(From DOE Document DE 9.3000001, November 1992)

Although sulfur is ultimately released to the atmosphere as the beds are regenerated, similar to thermal engine operation, less SOx will be released because less fuel is consumed per unit of energy produced.

When refineries begin to remove the sulfur prior to delivery, the sulfur control equipment can be reduced or removed from the fuel cell systems resulting in lower weight, volume, and cost. Also, if required, additional equipment could be added to store the sulfur onboard the ship instead of regenerating the beds by releasing SO_2 in the atmosphere.

CO and NMHC Emission

CO production is unavoidable in the combustion process of thermal engines. Fuel cells, however, produce no CO or Non-Methane Hydrocarbons (NMHC) in their exhaust gases. MCFC and SOFC plants actually use CO as a fuel. Gas turbine engine designers have not been required to address CO removal to date due to the small amount produced (20 ppm for LM2500[1] and 6.1 ppm for 501-K34 generator). This is not to say that in the future, requirements may necessitate its removal.

Particulate Emission

Fuel cell systems produce no particulates. Particulate emission in thermal engines usually stem from lubrication and hydraulic fluids entrained in the working fluid stream. There are no such fluids used in fuel cell systems. However, particulate emission regulation has not been a critical issue in naval power systems.

Fuel Conservation

One other environmental issue in which fuel cells have a part is fuel conservation. The potential for high operating efficiencies in fuel cell plants, upwards of 70% in some applications, is present. This, in turn, means potential energy savings or a lesser dependence on foreign crude.

2.5 Risk Analysis

Tables 2-6 and 2-7 present the results of risk analyses to determine the risk involved in developing the various fuel cell technologies for naval combatant service. Table 2-6 lists the performances levels considered achievable, as well as the development issues and advantages of the technology. Development of MC plants is considered low risk, however the plants have a low power density. PA fuel cell plant development is also considered low risk, however the power density is medium and long life has not been demonstrated. Development of PEM and tubular solid oxide technology is considered medium risk, and development of solid oxide planar technology is considered high risk. However, PEM and SO (planar) present a great potential for high power density.

Table 2-7 presents a subjective numerical assessment of the development issues and risk. The table lists issues that are considered in selecting a marine power plant and provides a weighing factor for each issue. The power plant types were then assigned a rating from 1 to 10 (10 = best) depending on how they satisfy the development issue. Using this method of risk assessment, the PEM and SOFC are judged to have the best potential, as seen in Figure 2-4.

[1]LM2500 produces up to 1000 ppm of NO_x at low loads.

Table 2-6

Fuel Cell Technology: State of Development and Risk

Type	Achievable for Combatants			Stage of Development of Landbased Plants		Issues	Advantages	Risk
	% Eff	lb/kW	ft^3/kW	Present (1993)	Future (2010)			
PEM	39 - 42	6.0 - 11.9	0.19 - 0.3	Low Power <120 kW Demos	Production >1000 kW	Water Balance Membrane Life CO Intolerant Low Efficiency	High Power Density Fast Start-Up Low Temp *High DP Capable	Medium
SO Planar	42 - 60	8 - 13.5	0.3 - 0.81	R&D	Production MW Plant	Very High Temp Seals Shock	High Efficiency CO Tolerant High Power Density *High DP Capable	High
SO Tubular	45 - 60	20 - 30	0.6 - 1.2	Pilot 44 - 100 kW	Production MW Plants	Very High Temp Low Power Density Shock	CO Tolerant *High DP Capable High Efficiency	Medium
MC	40 - 55	40 - 60	0.98 - 2.1	Engr Dev 250 kW	Production MW Plants	Low Power Density Long Start-Ups CO2 Balance Halide Control	CO Tolerant High Efficiency	Medium
PA	38 - 42	30 - 46	0.93 - 1.5	Production 11 MW	Production	CO Intolerant Med Start-Ups Corrosion Low Efficiency	Predictable Halide Tolerant	Low

*Differential Pressure (DP) refers to the pressure difference between the wall surfaces of a given cell.

Table 2-7

Assessment of Development Issues for Naval Fuel Cells (Operating on Diesel Fuel)

Assessment Weight	Issue	Fuel Cell Technology Rating (1 - 10)			
		MCFC	PAFC	PEM	SOFC
	Acquisition Cost				
0.8	Stack	5	6	4	2
0.8	BOP	6	2	2	6
	Acquisition Cost Reduction Potential				
0.8	Stack	4	6	8	8
0.8	BOP	7	6	6	8
	Life Expectancy Expansion Potential				
0.8	40,000 hrs	5	6	6	6
0.8	80,000 hrs	4	4	5	6
0.4	Overall Thermal Efficiency	6	4	4	8
	Shock and Vibration Sensitivity				
0.6	Stack	4	4	8	3
0.6	BOP	6	6	6	6
	Start-Up Time				
0.6	Cold Start	2	6	8	4
0.6	No. of Start Cycles	2	6	8	4
	Load Control				
0.6	Overload Sensitivity	6	6	8	7
0.6	Load Drop Sensitivity	2	4	2	8
	Overall Size/Weight				
0.6	Stack	2	6	6	6
0.6	BOP	8	5	4	6
	Overall Size/Weight Reduction Potential				
0.8	Stack	4	6	8	8
0.8	BOP	6	6	6	6
0.4	Salt Air Sensitivity	2	6	4	6
0.4	Sulfur Sensitivity	2	2	2	6

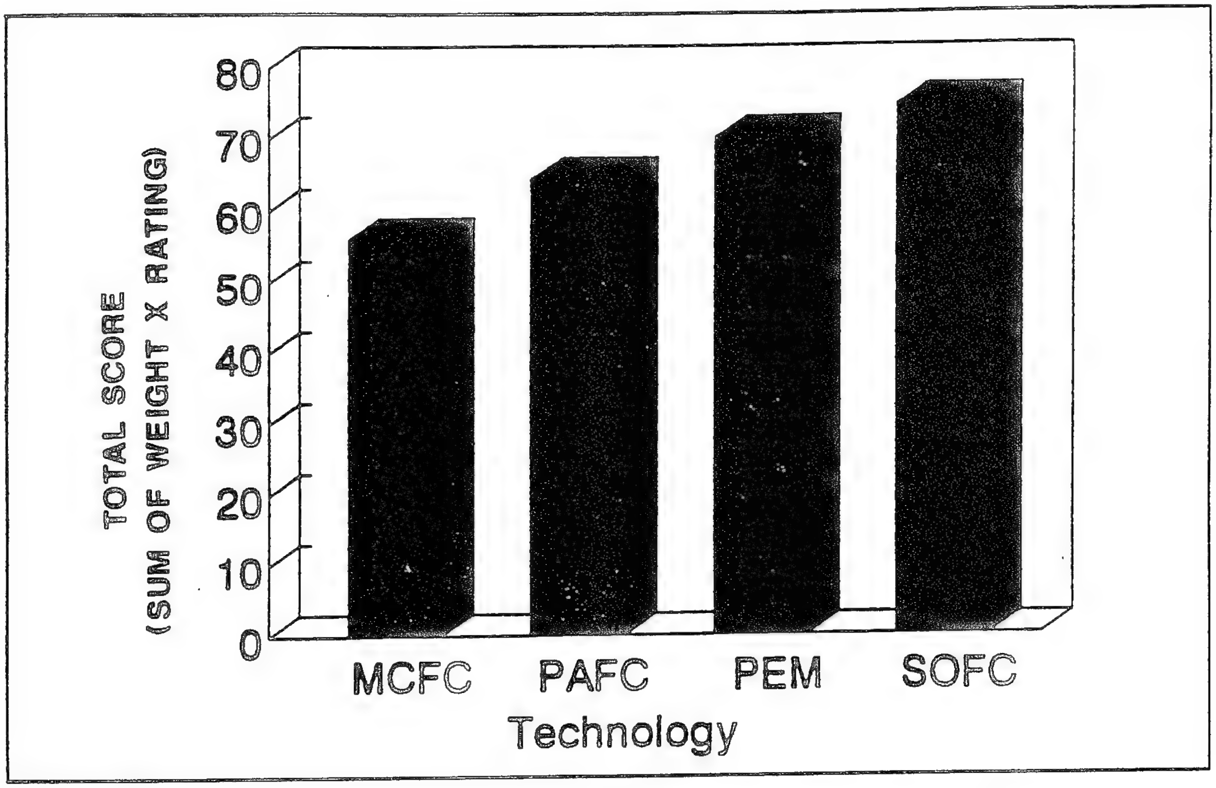


Figure 2-4. Fuel Cell Rating Score for Navy Development Issues (Based on Table 2-6)

CHAPTER 3

SHIP IMPACT

3.1 Introduction

This chapter examines the whole-ship impact of considering several types of fuel cell plants in several different applications for ships ranging in size from that of a Destroyer to that of a Corvette.

Of the surface combatants to be built in the near future for the U.S. Navy, many will likely be medium sized, multi-purpose destroyers or smaller corvettes. With this in mind, one of the two types of ships chosen as a baseline for this study was a Destroyer of approximately 5000 LT. To expedite the project, the baseline Destroyer was adapted from a design used in the DDV studies conducted during 1992. The Destroyer uses advanced technology systems expected to be available at the time fuel cell technology may be introduced.

The second ship considered as a baseline was a nominal 2000 LT corvette. Corvette size vessels may present less expensive alternatives than large combatants for small scale, regional conflicts that are expected to represent a large part of future Navy missions. It is also believed that this type of vessel presents a significant export potential for U.S. yards. The Corvette design was produced as a result of an analysis of the trends in the state-of-the-art in this range of size. The Corvette uses current off-the-shelf technology.

This chapter is intended to address three main questions. First, assuming that the Navy is interested in utilizing fuel cells for their inherent acoustic and environmental advantages, is the use of fuel cell power feasible for naval combatants? Second, if feasible for use, what are the impacts which will be seen aboard this type of naval ship? Third, considering the impact of the use of fuel cell power, what aspects of plant design impose the most significant impact on the ship?

Additional information that is not provided in the following sections regarding the characteristics of the baselines and fuel cell variants, can be found in Appendices C and D (C for Corvette and D for Destroyer).

3.2 Destroyer

3.2.1 Approach

The approach follows a typical method of assessing the impact of a new technology upon naval surface ships. Initially, a baseline model is developed. This baseline is modeled to resemble the most likely state-of-the-art design for the ship type under consideration at the time the new technology is intended to be introduced. Once the baseline model is assembled, the new technology is incorporated into the baseline model and a new, balanced design is created. After these models are constructed, an analysis is conducted to determine what changes were introduced into the design due to the new technology and why they occurred.

In order to assess the impact of several different fuel cell types, applied in several arrangements aboard the ship, a computerized ship synthesis model was used to develop the Destroyer Baseline and all of the variations incorporating fuel cells.

The Destroyer Baseline model was developed using the Advanced Surface Ship Evaluation Tool (ASSET). ASSET is a ship synthesis program which allows the designer to build a computer model describing a ship and all the systems aboard the ship. The designer can then incorporate the description of a new technology into the ship model and determine the impacts upon the overall ship design as a result of the addition of that technology.

Some manual control was exercised over the alteration of the Destroyer baseline hull form for the variants. In order to rely on the comparison of technical benefit between a baseline and technology variants, it is important to ensure consistency in design between the baseline and the variants. It is important to make only changes that are directly related to the new technology and not to introduce design changes that result in an improvement or detriment in performance or cost that are not directly related to the new technology.

A specific methodology has been developed for hull form modifications to ensure consistency. The Length-to-Displacement ratio is maintained constant for all designs. This method is described further in Appendix D. It allows for consistency between designs while accounting for the impact the new technology has upon each variant's displacement and dimensions.

Baselines and Variants Examined

The Destroyer Baseline has an electric drive propulsion system consisting of two Intercooled Recuperated (ICR) gas turbine generators as main power sources. The ship service power under normal conditions is drawn directly from the power produced by the ICR and distributed throughout the ship as DC power. The baseline also has one separate gas turbine ship service generator set. This provides a standby source for ship service power if the main ICR gas turbines are not running.

In order to gain an initial picture of the possible impact that fuel cell technology has upon this destroyer design, fuel cell power systems were used in place of baseline power production machinery in several different configurations. The configurations consisted of:

- A direct replacement of the separate ship service generator set with a fuel cell system which still acts only as a standby power source.
- The replacement of the separate ship service generator set with three identical fuel cell systems which will then provide all of the required ship service power. Ship service power is no longer drawn away from the power produced by the ICR gas turbine generator sets.
- The replacement of the separate ship service generator set and the two ICR gas turbine generator sets with one small fuel cell system as the standby power source and two larger fuel cell systems providing all of the main propulsion power as well as ship service power.
- The replacement of the separate ship service generator set with twelve identical fuel cell systems which are distributed throughout five distinct electrical zones. These twelve fuel cell systems will then provide all of the required ship service power. Ship service power is no longer drawn away from the power produced by the ICR gas turbine generator sets.

A second baseline using a distributed ship service power system with 12 diesel generators distributed in five distinct electrical zones was also established for comparison with the fuel cell variant with distributed ship service power. Ship service power in this second baseline is no longer drawn away from the power produced by the ICR gas turbine generator sets. Table 3-1 illustrates the machinery suits used in the baselines and variants of the destroyer.

In addition, it was felt that a likely potential use for fuel cells will be as a backfit replacement of older generator sets. To examine this potential impact, a baseline model of the DDG 51 class destroyer was used. The DDG 51 backfit variant has a fuel cell system replacing each of the three separate ship service gas turbine generator sets.

All of the above variants were repeated for each of the different fuel cell technologies being examined in this study, that is:

- Proton Exchange Membrane (PEM)
- Phosphoric Acid (PA)

- Molten Carbonate (MC)
- Solid Oxide (SO).

Table 3-1

Destroyer Machinery Suites, Baselines and Variants

	Propulsion	Ship Service
Baseline	IPS 2 ICR Gas Turbines 2 PM Generators/Motors	DC Distribution 2 PDSS (GT) 1 Standby GT Genset
Standby Ship Service Variants	IPS 2 ICR Gas Turbines 2 PM Generators/Motors	DC Distribution 2 PDSS (GT) 1 Standby Fuel Cell Unit
Ship Service Variants	IPS 2 ICR Gas Turbines 2 PM Generators/Motors	DC Distribution 3 Fuel Cell Units
Propulsion Variants	IPS 2 Fuel Cell Units 2 PM Motors	DC Distribution 2 PDSS (Fuel Cell) 1 Standby Fuel Cell Unit
Distributed Baseline	IPS 2 ICR Gas Turbines 2 PM Generators/Motors	DC Distribution 12 Diesel Generators (Distributed Through Five Distinct Zones)
Distributed Ship Service Variants	IPS 2 ICR Gas Turbines 2PM Generators/Motors	DC Distribution 12 Fuel Cell Units (Distributed Through Five Distinct Zones)

Design Requirements

The Destroyer Baseline and its variants are intended to be multi-purpose assets supporting the U.S. Navy fleet in all areas of the world. The primary missions for the Destroyer include all those of a modern destroyer of the U.S. Navy:

- Anti-Air Warfare Operations
- Anti-Surface Warfare Operations
- Anti-Submarine Warfare Operations
- Shore Bombardment to Support Amphibious Operations

In light of the rapidly changing roles to be played by the U.S. Navy and the fact that destroyers and smaller ships will make up the bulk of our expected combatant new buildings in the near future, some additional missions for the Destroyer could include:

- Escort and Support of Fast Sealift and Supply Ships
- Emergency Rescue or Support Operations
- Support Coast Guard in Law Enforcement/EEZ Patrol

The Destroyer will need to be a versatile combatant, capable of performing these operations on its own or when operating in conjunction with other ships. It will also likely be required to perform these varied missions in both blue-water, full-scale war and in littoral, limited-objective situations.

These factors led to the decision to use the DDS Destroyer, which was part of a Navy conceptual design exercise performed during 1992, as the starting point for developing the Destroyer baseline. The Destroyer Baseline was adapted from the electric drive version of the DDS Destroyer, using similar initial dimensions, payloads and arrangements.

Design Standards and Margins

Unless otherwise specified, the design standards and margin values of the U.S. Navy were applied to the Destroyer Baseline and its variants. Table 3-2 summarizes the principal design and service life margins used when producing the ship variant designs.

Table 3-2

Destroyer Design and Service Life Margins

Item	Description
Weight (Design and Construction)	10% of lightship weight (sum of SWBS 100 to 700) added for design and construction margin
KG (Design and Construction)	10% of lightship condition KG added for design and construction margin
Accommodations	10% added to the manning
Electric Plant (Design and Construction)	20% design margin added to the maximum electric load, then 20% service life margin added to find total margined electric load
Propulsion Power	8% added to hull and appendage EHP
Endurance Fuel	Per Design Data Sheet DDS-200-1

Mission Profile and Fuel Load

As part of the overall ship impact, it was desired to determine how the use of fuel cells would affect the fuel economy of the destroyer variants. Two different areas of the ship performance where the fuel economy will have an impact are the fuel required to meet the design range and the total fuel used during the normal execution of an extended mission.

The design condition for the Destroyer baseline requires that the destroyer be able to sail 5000 nautical miles at 20 knots. This requirement will establish the amount of usable fuel that is required to be stored aboard the ship. Considering a 95 per cent usable fuel factor, a required fuel load is determined.

The fuel economy of the power plants will also affect the total fuel used over the course of a period at sea. Table 3-3 presents a notional mission profile for the Destroyer. The purpose of this notional profile is to provide a common reference for comparison between the baselines and each of their variants.

Table 3-3

Destroyer Notional Mission Profile

Hours at Anchor	1500
Hours Underway	2700
SPEED	PERCENTAGE
11	27.2
15	28.7
19	37.3
23	4.5
27	2.3

3.2.2 Destroyer Baselines

Three baselines were used in the destroyer section of the fuel cell impact study. The Destroyer baseline, which is used as the baseline for most of the variants examined, is described in this section. A second baseline using distributed ship service diesel generators was developed and is described briefly in Section 3.2.2.2. In addition, a model of the DDG 51 was used as the baseline for the study of the DDG 51 class ship service power backfit. This additional baseline is discussed in Section 3.2.2.3.

3.2.2.1 Destroyer Baseline (Standard)

General Characteristics

The ship particulars of the Destroyer Baseline are presented in Table 3-4.

Table 3-4

Destroyer Baseline General Characteristics

Overall Length, ft	447.0
LBP,ft	425.0
Beam at DWL, ft	55.4
Depth, ft	32.8
Draft, ft	16.0
Freeboard (midships), ft	21.1
Full Load Displacement, LT	5270
GMt, ft	5.7
Midship Coefficient	0.801
Prismatic Coefficient	0.598

Manning

The manning level of the Destroyer Baseline was retained from the DDS Destroyer. This manning level was set at an estimated minimum level which could still effectively maneuver and fight the ship as well as operate the communications systems. In addition, the personnel required for the operation and maintenance of the embarked helicopter are included. The accommodations aboard the Destroyer Baseline include a 10 percent margin for future growth and mission flexibility. The assumed manning level of the Destroyer Baseline can be seen in Table 3-5. The same manning level was assumed for the fuel cell variants as no criteria was identified that would require more or less personnel to operate and maintain a fuel cell plant.

Table 3-5

Destroyer Manning and Accommodations

	Ships Crew	Air Detachment	Total Manning	Total Accommodations
Officers	18	4	22	24
CPO	12	3	15	17
Enlisted	160	8	168	184
Total	190	15	205	225

Combat Systems

The Destroyer Baseline carries all the weapons and sensors which are required for the ship to effectively carry out its missions involving Anti-Surface, Anti-Air, and Anti-Submarine Warfare. In addition, the Destroyer Baseline will be expected to support amphibious operations. The weapons, sensors, and associated systems involved in the Destroyer Baseline combat suite include:

- Combat Information Center Equipment
- Identification and Communication Equipment
- Surface Search and Multi-function Search and Track Radars
- Electronic Warfare and Countermeasures Systems
- Hull Sonar and Towed-Array Sonar Systems
- ASUW, AAW, and ASW Fire Control Systems
- One SH-60B Helicopter Including Armament and Aviation Support Systems
- Torpedo Systems with 12 OTS Torpedoes
- One 5"/54 Gun with Ammunition
- Two Mk 16 CIWS with Weapon Control Systems, Workshops, and Ammunition
- One Mk 41 48-Cell VLS with Missile Loadout
- Small Arms and Ammunition

These payload items are accounted for in detail within Ship Work Breakdown Structure (SWBS) Groups 100, 400, 500, 600, 700 and F00. Taken as a whole, they contribute approximately 700 LT and 12,700 ft^2 of required area to the Destroyer baseline model. The same payload items were also required on all the fuel cell variants.

Propulsion/Electric Plant

Fuel cell technologies are not expected to be integrated into U.S. Navy combatants for at least ten to fifteen years. In order to achieve the most realistic calculation of the impact of fuel cell systems on the Destroyer

baseline, the baseline should include the machinery systems which will most likely be in use for new ships at that time. For this reason an integrated electric propulsion system was used in the model for the Destroyer Baseline. Electric drive is seen as the probable propulsion system for future combatant ships.

The Destroyer Baseline incorporates the Integrated Power System (IPS). The IPS system uses two inter-cooled recuperated (ICR) gas turbines as its main power source. These ICR gas turbines each produce 26,400 hp. The ICR gas turbines drive permanent magnet generators which feed DC electricity into the DC propulsion bus. The DC propulsion bus feeds electric power to two permanent magnet electric motors each of which is directly connected to a 14-foot fixed-pitch propeller.

The electric power required for the combat systems and ship service power is provided by three generators. There is a solid state propulsion derived ship service (PDSS) generator drawing power from each of the ICR gas turbines. Each of the PDSS is rated at 2500 kW. In addition, there is a separate ship service generator. This gas turbine generator set is also rated at 2500 kW. Each of these generators feeds DC electric power to the DC ship service distribution system which connects each of the watertight subdivisions in the Destroyer Baseline. Inverters are located in each of the watertight subdivisions to provide the necessary AC power. Table 3-6 presents the electric loads for the Destroyer Baseline.

The IPS system is currently under development by the U.S. Navy Advanced Machinery Systems Program.

Table 3-6

Destroyer Baseline Electric Loads (kW)

Maximum Margined Electric Load,	3887
Maximum Standby Load,	2115
24 Hour Average Electric Load,	1564

Weight Breakdown

The ASSET program follows the U.S. Navy's SWBS classification system for weights. The summary weights for the Destroyer Baseline are shown in Table 3-7. The weights which were input to or calculated by ASSET are shown in Appendix D to the 3-digit level.

Arrangements

The arrangements of the Destroyer Baseline were kept essentially the same as the DDS Destroyer. There was only minimal effort expended to ensure that the ship had an optimal subdivision considering the machinery, sensor, and weapon systems aboard the ship. Essentially, the deck areas required by all of the payload items mentioned previously were included in the total required area for the ship. The iterations through the design cycle within ASSET are intended to adjust the dimensions of the ship's hull and deckhouse such that the available internal deck area is greater than or equal to the required area.

It is assumed that a more rigorous investigation of the arrangement requirements of all the payload items would result in changes to the Destroyer baseline model. However, this rigorous effort was not included in this study since the focus is on the impact to the ship due to changes in the machinery systems.

The two ICR gas turbines and PDSS generators are located in a single main machinery space in order to reduce the size of the ship. This reduction in ship size leads to a reduced cost for the ship. This main machinery space is located midships in the Destroyer Baseline. The two propulsion motors are located

in an auxiliary machinery room directly aft of the main machinery room. The separate ship service generator is located in an auxiliary machinery room located in the forward end of the ship.

Table 3-7

Destroyer Baseline Weight Summary

SWBS Category	Weight, LT
SWBS 100 - Hull Structure	1708
SWBS 200 - Propulsion Plant	446
SWBS 300 - Electric Plant	157
SWBS 400 - Command and Control	257
SWBS 500 - Auxiliary Systems	626
SWBS 600 - Outfit and Furnishings	476
SWBS 700 - Armament	190
Sum of SWBS 100 - SWBS 700	3858
Margin	386
Lightship Displacement	4244
Full Loads	1025
Full Load Displacement	5269

The ASSET program will keep track of the total internal deck area and volume required by the personnel and systems aboard the ship and will adjust the dimensions of the ship and the deckhouse to achieve a balanced design. No effort was made in this study to shape or size the deckhouse for any reason other than for achieving the required internal volume. This is expected to allow a better assessment of the volumetric impacts of the fuel cell technologies.

The machinery arrangement of the Destroyer Baseline is presented in Figure 3-1.

Performance

The Destroyer Baseline is expected to operate in all areas of the world both alone and in conjunction with other ships in Carrier Battle Groups, Amphibious Groups, or Surface Action Groups. The general performance characteristics of the Destroyer Baseline are shown in Table 3-8.

3.2.2.2 Distributed (Ship Service Power) Baseline Destroyer

The Distributed Ship Service baseline is intended to provide a proper reference to assess the impact fuel cell systems would have upon a ship service power system with individual power sources distributed throughout the ship. This study of a distributed system provides only a first estimate of the impact of a distributed system aboard the Destroyer Baseline. For this baseline, all of the ship service power requirements are met by 12 diesel generators rated at 500 kW. These 12 units are distributed among five separate electrical zones. The arrangement of the electrical zones within the distributed ship service variant was modified from the electrical zones of the DDG 51 as defined by the Advanced Machinery Systems Program.

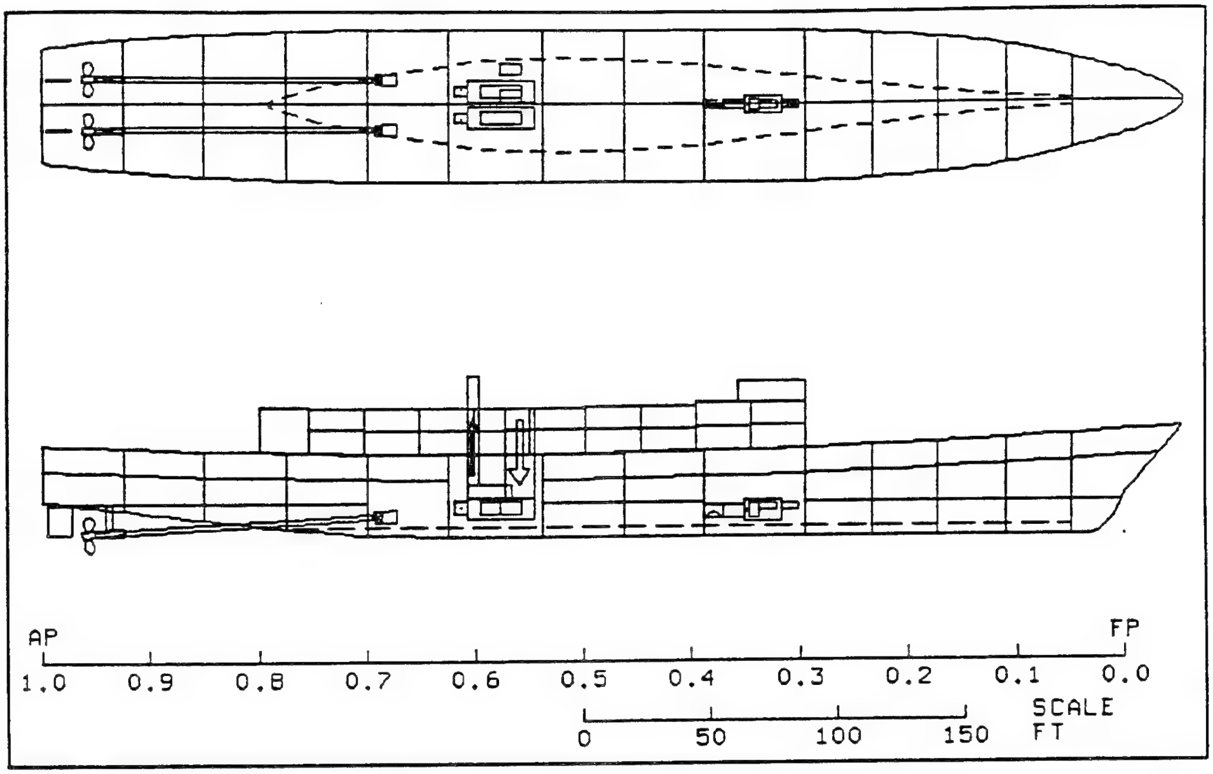


Figure 3-1. Machinery Arrangement of the Destroyer Baseline

Table 3-8

Performance Characteristics, Destroyer Baseline

Maximum Speed, kts	28.1
Sustained Speed, kts	26.9
Endurance Speed, kts	20.0
Range at Endurance Speed, NM	5000

The machinery arrangement of the Distributed SS Baseline for the Destroyer is shown in Figure 3-2.

The IPS machinery system of the Destroyer Baseline already has a highly redundant DC distribution system for the ship service electrical system. This distribution system was left unchanged in this variant so that each electrical zone can supply excess power to any other zone that happens to lose its power source in some manner.

3.2.2.3 DDG 51 Class Baseline

It is felt that one of the earliest potential uses for fuel cell power systems aboard naval surface ships will be as replacements for less efficient ship service power generators. With this in mind, it was decided to also examine the impact of fuel cell systems used as backfit replacements of the separate ship service generators aboard the DDG 51 class of destroyers.

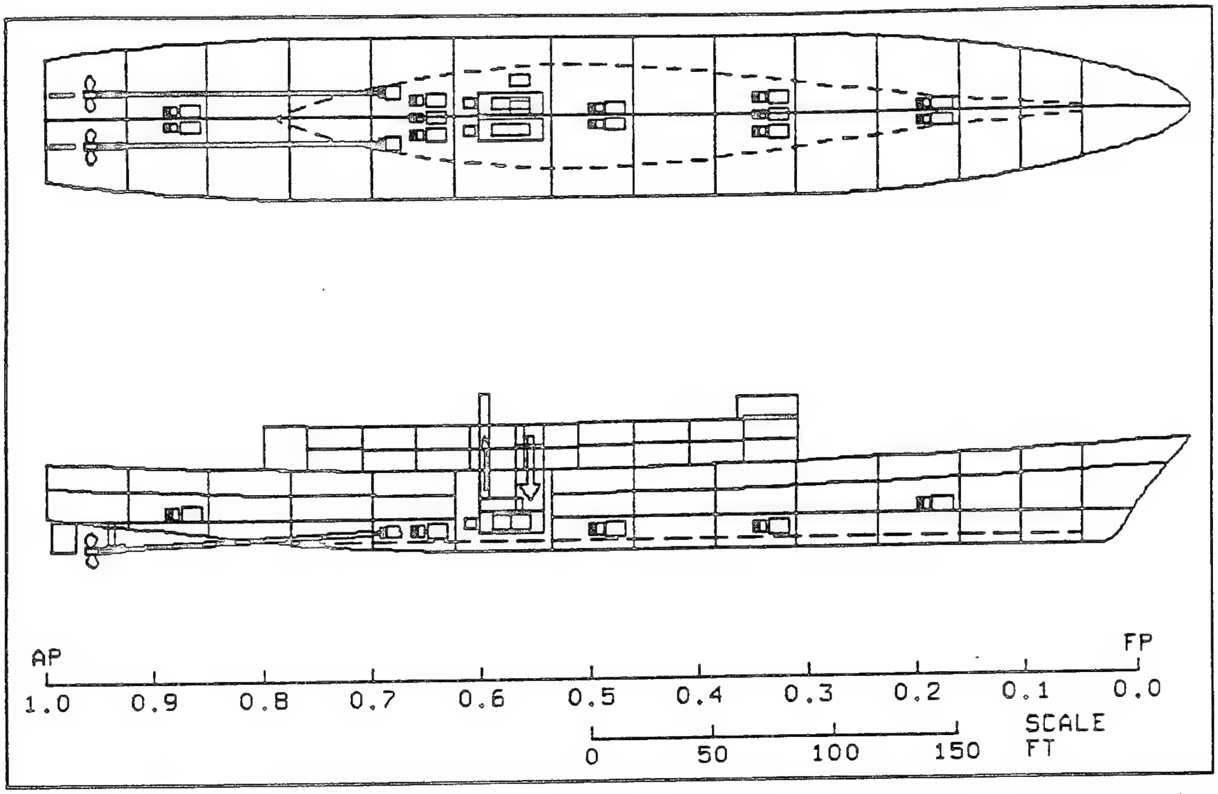


Figure 3-2. Machinery Arrangement of the Distributed SS Destroyer Baseline

The existing ASSET model of the DDG 51 was used for the baseline model in this comparison. The ship service electric plant aboard the DDG 51 consists of three 2500 kW Allison 501k-17 gas turbine generating sets. These generator sets are located one each in the two main engine rooms plus one in a separate auxiliary generator room. The ship service electrical system aboard the DDG 51 is an AC system.

3.2.3 Destroyer Parametric Analysis

The purpose of the parametric analysis was to identify characteristics of the fuel cell plants that have the greatest impact on the characteristics of a balanced ship design.

The results of the parametrics also provide guidance to allow manufacturers to immediately assess the pay-offs resulting from design changes and to set goals in order to make fuel cells practical for Navy use.

The parametric study assumed a generic fuel cell defined by three basic parameters:

- Plant Density - lb/ft^3
- Weight-to-Power Ratio - lb/kW (inverse from power density)
- Specific Fuel Consumption - lb/kW-hr

The volume of the fuel cell plants varied proportionately with weight for a given plant density and is, therefore, inherently accounted for by the parameters above.

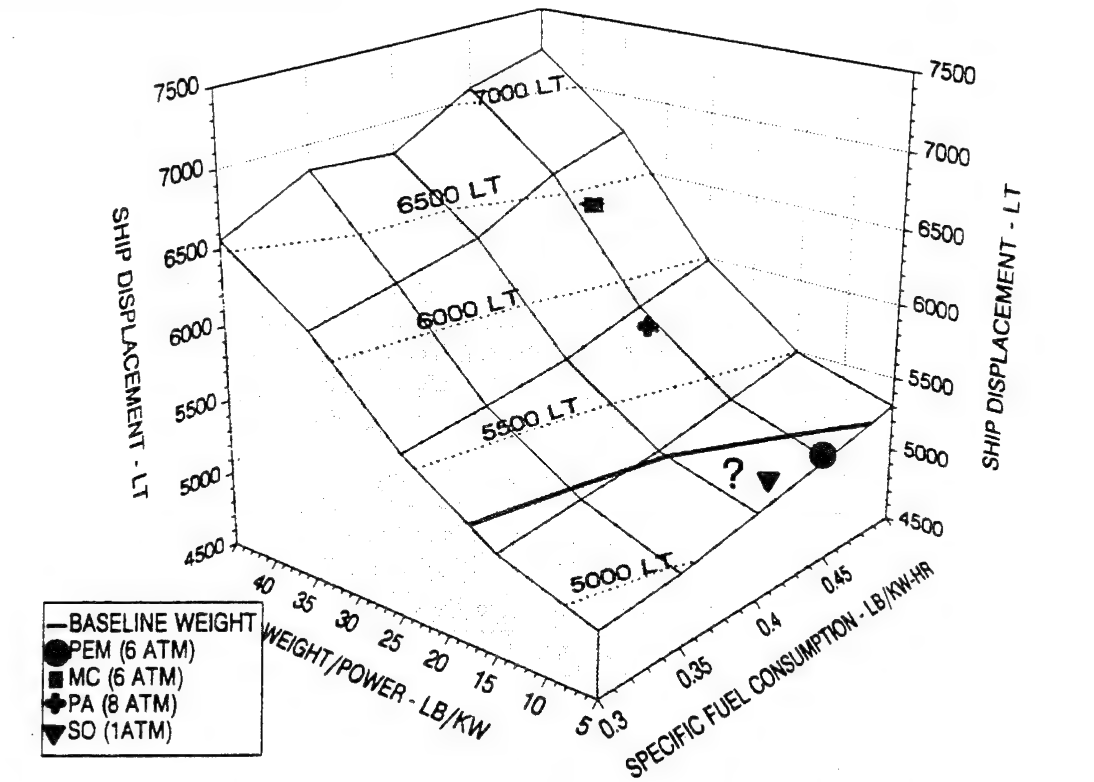
It was found that plant density had only a second order effect on the trends. Since most of the plants studied had a density around 30 to 40 lb/ft^3, a value of 30 lb/ft^3 was retained for this analysis as representative of the fuel cell plants considered.

It should be noted that the shape of the specific fuel consumption curve as a function of plant loading was assumed to be identical, in the destroyer parametric study, to that of a diesel engine. The actual shape was found to be dependent upon the fuel cell type in Chapter 2 and, therefore, the parametrics should be viewed as providing first order results indicating approximate trends only.

The carpet plots presented in this section examine the (integrated) propulsion variant of the Destroyer for which the clearest trends can be seen. In this variant, fuel cell systems are used to provide all of the electrical power used for both propulsion and ship service power. In addition, the results are presented only for the impact upon the total ship displacement. The changes in the ship displacement provide a good estimate of what the impact of the potential fuel cell technology will be on other ship aspects such as dimensions, volume, power and cost.

The carpet plots, shown in Appendix D present the effect of the variation of all three aspects of the fuel cell technologies mentioned above upon the displacement of the propulsion variant. Figure 3-3 shows a typical carpet plot for a plant density of 30 lb/ft^3.

The vertical axis shown in Figure 3-3 shows how the displacement varies with the two primary fuel cell parameters. Across the range investigated, it can be seen that the weight-to-power ratio shows the largest impact while the specific fuel consumption is found to have a lesser influence. These results could lead developers of different fuel cell technologies to focus more research and development efforts on the reduction of the weight-to-power ratio.



NOTE: THE ? SYMBOL, BESIDE THE SOFC DATA POINT, MEANS VERIFICATION IS NEEDED.

Figure 3-3. Ship Displacement Versus Power Density and SFC, Plant Density = 30 lb/ft^3, Destroyer

The displacement of the baseline (5270 LT) is shown across the plot and was considered as a threshold for a positive ship impact on the overall design.

The four fuel cell types considered in this study are also plotted on Figure 3-3 using the data determined during the technology characterization (see Chapter 2). It can be seen that Molten Carbonate and Phosphoric Acid fuel cells have too large a weight-to-power ratio to present benefits to a Destroyer size vessel, from a ship impact point of view. Note that this conclusion would remain the same even if their specific fuel consumption was reduced by incorporating a bottoming cycle (heat recovery system). It can also be seen that Planar Solid Oxide and Proton Exchange membrane fuel cells offer a good potential for a positive ship impact. Note that a bottoming cycle may be applied to the Solid Oxide fuel cells which operate at high temperatures while it is most likely not to be used with a Proton Exchange Membrane fuel cell due to its low operating temperature. Thus, Planar Solid Oxide fuel cells present the greatest potential for positive ship impact of all four types of fuel cells investigated. However, it is also the least advanced as far as its development is concerned and the data available for this fuel cell type are not as reliable as that of the other types.

3.2.4 Destroyer Point Designs Study

The specific characteristics of each fuel cell type was incorporated into the design synthesis model (ASSET) used in this study and destroyer point designs were developed for each application and each fuel cell type (except Solid Oxide for lack of reliable data). The principal results and findings are provided in this section.

3.2.4.1 Proton Exchange Membrane Fuel Cell Variant Designs

The significant ship impacts resulting from incorporating PEM fuel cell systems into the Destroyer variants are presented in Table 3-9.

PEM Standby Ship Service Variant

The Standby Ship Service Variant is seen as the most probable variant for the initial application of fuel cells to U.S. Naval ships. In this variant, a single fuel cell power system, of equivalent power output, is used in place of the separate Allison 501-K17 ship service gas turbine generator. The focus of this variant is to make a relatively straight forward replacement of the gas turbine to take advantage of the fuel cell's lower fuel consumption. The characteristics used for each of the different fuel cell types examined was presented previously in Chapter 2. The fuel cell unit was located within the model in the same location as the original gas turbine generator set.

The original gas turbine generator set was only used to produce power under emergency situations and while the ship is at anchor and the main propulsion units are off-line. During normal ship operations underway, the propulsion and ship service power will continue to be provided by the Integrated Power System as described in the previous section on the Destroyer Baseline.

If fuel cells are going to be used for a standby application in the future, an important issue to be addressed is the start-up time required by each of the different fuel cell technologies. Reduced start-up times are especially important for fuel cell units required to respond to emergency situations. The aspect of start-up times has not been addressed in detail during this study.

From an initial ship impact point of view, the use of PEM fuel cells in the Standby Ship Service Variant has several small, positive ship impacts.

The PEM fuel cell had a small positive impact on the size of the variant ship. The weight of the electric plant (SWBS 300) is reduced by 24 LT. In addition, the reduced size of the fuel cell plant leads to a reduction in the required machinery room volume of nearly 3700 ft^3. In combination, these two impacts lead to a reduction in the overall ship displacement of 43 LT.

Table 3-9

Proton Exchange Membrane Fuel Cell Ship Impact Results, Destroyer

	Units	Baseline	Standby Ship Service Variant	Ship Service Variant (Centralized)	Propulsion Variant	Distributed Ship Service Variant	Distributed Baseline
Displacement		5269	5226	5342	5219	5556	6093
Length Between Perp.	feet	425	423.8	427	423.6	432.6	446.1
Propulsion Plant Weight	LT	446	446	451	537	452	457
Electric Plant Weight	LT	157	133	157	127	161	399
Total Fuel Weight	LT	664	663	687	623	717	767
Installed Prop. GT Power	kW	39389[1]	39389[1]	39389	0	39389	39389
Installed SS GT/DG Power	kW	2500 (GT)	0	0	0	0	6029(DG)
Installed Fuel Cell Power	kW	0	2512	7536	40027[2]	6029	0
Maximum Electric Load	kW	3887	3915	3974	3827	4260	4362
Maximum Speed	Kts	-	+0.0	+0.5	+0.0	+0.3	+0.2
Total Fuel Used - w/ M.P.	LT	5588	5134	5291	4630	5447	6089
Prop. Plant Req. Vol.	$feet^3$	87747	87945	88013	84001	87902	88322
Electric Plant Req. Vol.	$feet^3$	32113	28461	35240	28214	79252	94559
Auxiliary Mach. Req. Vol.	$feet^3$	44918	44687	44767	46916	44844	45642
Fuel Tankage Vol.	$feet^3$	28066	28026	29078	26357	30331	32432
Req. Duct Vol.	$feet^3$	12523	9373	9990	5146	10757	15055
Total Machinery Volume	$feet^3$	205367	198492	207088	190634	253086	276010

[1] Includes 5000 kW Ship Service Power.
[2] Includes 7500 kW Ship Service Power.

There were two more significant impacts with PEM fuel cells in this variant. First, due to the improved specific fuel consumption the total fuel used during the notional mission profile (six months deployment) was reduced by 454 LT. This will save a substantial amount of fuel over the service life of the ship. Second, due to the reduced exhaust flow and temperature, the required volume of the intake and exhaust ducts outside of the machinery spaces is reduced by 3150 ft^3. This contributed to the reduced overall volume of the ship variant.

PEM Ship Service Variant (Centralized)

The (Centralized) Ship Service Power variant is intended to demonstrate the impact upon the Destroyer Baseline when fuel cell systems are used to provide the ship service power isolated from the original main propulsion power. In this variant, three 2500 kW fuel cell units are used to produce all of the required ship service power. These three units are direct replacements for the two solid state PDSS generators and one separate gas turbine generator found in the baseline.

The fuel cell units replacing the solid-state PDSS are located within the auxiliary machinery room containing the propulsion motors. The fuel cell unit replacing the separate gas turbine generator is located in the same space as the gas turbine in the baseline. Since this is a centralized ship service arrangement, the DC power produced by the fuel cell systems is still fed into the original DC ship service distribution system.

This variant is not considered to be a likely application of the fuel cell technology since it is giving up many of the advantages gained by combining the propulsion and ship service power. However, it provides improved survivability (power plants distributed in three compartments instead of two) and increased power for propulsion (5000 kW).

The installation of PEM fuel cells on the (Centralized) Ship Service variant had a relatively small impact on the baseline ship.

Since all of the ship service power is being provided by the fuel cell units, there are three separate fuel cell units. These units have a weight and volume impact on the ship which the solid state propulsion derived ship service power source did not have. The increase of 3127 ft^3 in the volume required for the electric plant machinery room lead to an increase in the ship size. Thus, the displacement was increased by 73 LT. Some of the increase in the electric plant volume was offset by decreases in deckhouse volume due to a decrease of 2533 ft^3 in the volume required for intake and exhaust ducting.

The increased fuel efficiency of the fuel cells used when the ship is at anchor leads to fuel savings of 297 LT through the destroyer mission profile.

An additional effect of isolating all of the ship service power in the fuel cell units was an increase in maximum speed of 0.5 knots. When the ship service power is no longer drawn from the ICR gas turbine generator units, all of the gas turbine power can be used for propulsion. Under the assumption that the rating of the ICR would remain unchanged, an extra 5000 kW was available for propulsion.

The spread of the power plants in three compartments instead of two also improves the survivability of the vessel.

PEM Propulsion Variant

The Propulsion Power variant demonstrates the impact upon the Destroyer Baseline when Fuel Cell systems are used to replace all propulsion and ship service power sources on the ship. One 2500 kW Fuel Cell unit replaces the separate ship service generator set. The two ICR gas turbine generator sets are replaced with fuel cell units of approximately similar power levels. All the fuel cell units are placed in the same location as the gas turbines they are replacing.

Similar to the Destroyer Baseline, all of the propulsion and ship service power requirements are met by the two large propulsion fuel cell units during normal operating conditions. The separate, smaller fuel cell unit only provides power during emergencies and while the ship is at anchor.

The power levels of the main propulsion fuel cell units were adjusted so that the Propulsion variant had the same speed characteristics as the baseline. This will provide better data for the subsequent cost comparison between ships with similar performance characteristics.

The use of PEM fuel cells aboard the Propulsion variant caused a decrease in the weight of the electric plant of 30 LT. However, this was offset by an increase in the propulsion plant weight of 91 LT. Overall, the Propulsion Power variant was slightly smaller and 50 LT lighter than the baseline. A large part of this reduction was due to a decrease of 7647 ft^3 in the required volume for the machinery rooms and a significant decrease of 7377 ft^3 in required intake and exhaust ducting.

The fuel capacity of the ship required to meet the design range of 5000 NM was reduced by 41 LT. In addition, the combination of a reduced ship size, and increased fuel efficiency of both the propulsion and ship service power generators, lead to a reduction of 958 LT in total fuel used in the mission profile. Operationally, this also means that the Destroyer will require refuelling less often, and with a lesser amount. This will give the task group commander increased flexibility in scheduling the logistics of his refuelling ships.

PEM Distributed Ship Service Variant

The 12 diesel generators from the distributed baseline are replaced in this variant by fuel cell units which are all independent units. Each unit has its own associated balance-of-plant and desulfurizing equipment. In future studies of distributed systems, however, savings in weight and volume of the electrical plant can

be achieved by combining the balance of plant equipment for all the fuel cell units which are co-located within a single electrical zone.

The Distributed Ship Service Power variant demonstrated the real advantages of using PEM fuel cells instead of diesel generators in a distributed ship service system. The Distributed variant was 13.5 feet shorter and 537 LT lighter than the diesel generator distributed baseline.

Three significant factors lead to this reduction in size and displacement. The weight of the electric plant was reduced 238 LT, the required volume for the machinery space of the electric plant was reduced by 15,307 ft^3, and the required volume for intake and exhaust ducting was reduced by 4300 ft^3.

The increase in fuel efficiency with the fuel cells improved the ship impact by reducing the fuel required to meet the mission profile by 642 LT and the fuel tankage required to meet the design range of 5000 NM by 50 LT.

3.2.4.2 Molten Carbonate Fuel Cell Variant Designs

The significant ship impacts resulting from incorporating MC fuel cell systems into the Destroyer variants are presented in Table 3-10.

Table 3-10

Molten Carbonate Fuel Cell Ship Impact Results, Destroyer

	Units	Baseline	Standby Ship Service Variant	Ship Service Variant (Centralized)	Propulsion Variant	Distributed Ship Service Variant	Distributed Baseline
Displacement	LT	5269	5350	5703	7550	6198	6093
Length Between Perp.	feet	425	427.2	436.4	479.2	448.7	446.1
Propulsion Plant Weight	LT	446	446	454	1236	457	457
Electric Plant Weight	LT	157	189	326	197	393	399
Total Fuel Weight	LT	864	668	705	1025	757	767
Installed Prop. GT Power	kW	39389[1]	39389[1]	39389	0	39389	39389
Installed SS GT/DG Power	kW	2500 (GT)	0	0	0	0	6029(DG)
Installed Fuel Cell Power	kW	0	2500	7500	44500[2]	6000	0
Maximum Electric Load	kW	3887	3932	4030	4270	4502	4362
Maximum Speed	Kts	-	-0.1	+0.4	+0.0	+0.1	+0.2
Total Fuel Used - w/ M.P.	LT	5588	5217	5457	7062	5855	6089
Prop. Plant Req. Vol.	$feet^3$	87747	88107	88441	137136	88236	88322
Electric Plant Req. Vol.	$feet^3$	32113	31295	43820	33461	134176	94559
Auxiliary Mach. Req. Vol.	$feet^3$	44918	44900	45328	53081	45633	45642
Fuel Tankage Vol.	$feet^3$	28066	28238	29830	43372	32013	32432
Req. Duct Vol.	$feet^3$	12523	9413	10223	4652	10965	15055
Total Machinery Volume	$feet^3$	205367	201953	217642	271702	311023	276010

[1] Includes 5000 kW Ship Service Power. [2] Includes 7500 kW Ship Service Power.

Although similar results as for the PEM variants are found regarding the reduction of intake/exhaust duct volume, the machinery weight and volume was increased for all the variants due to the low power density of the Molten Carbonate fuel cells. Fuel savings through the mission profile are also seen except in the propulsion replacement variant which increased significantly in size, weight and power compared to the baseline.

3.2.4.3 Phosphoric Acid Fuel Cell Variant Designs

The significant ship impacts resulting from incorporating PAFC systems into the Destroyer variants are presented in Table 3-11. The results for the PAFC variants follow similar trends to that of the MCFC variants. However, the negative impact, especially in the propulsion variant, is of a lesser amplitude as the PAFC power density is intermediate between that of the PEMFC and of the MCFC.

Table 3-11

Phosphoric Acid Fuel Cell Ship Impact Results, Destroyer

	Units	Baseline	Standby Ship Service Variant	Ship Service Variant (Centralized)	Propulsion Variant	Distributed Ship Service Variant	Distributed Baseline
Displacement	LT	5269	5344	5671	6520	6050	6093
Length Between Perp.	feet	425	427	435.6	456.3	445.3	446.1
Propulsion Plant Weight	LT	446	446	454	981	456	457
Electric Plant Weight	LT	157	186	317	184	345	399
Total Fuel Weight	LT	664	667	694	819	738	767
Installed Prop. GT Power	kW	39389[1]	39389[1]	39389	0	39389	39389
Installed SS GT/DG Power	kW	2500 (GT)	5000	0	0	0	6029(DG)
Installed Fuel Cell Power	kW	0	2500	7500	42500[2]	6000	0
Maximum Electric Load	kW	3887	3930	4023	3958	4449	4362
Maximum Speed	Kts	-	-0.1	+0.4	+0.0	+0.1	+0.2
Total Fuel Used - w/ M.P.	LT	5588	5213	5349	5805	5770	6089
Prop. Plant Req. Vol.	$feet^3$	87747	88101	88394	119879	88123	88322
Electric Plant Req. Vol.	$feet^3$	32113	31005	42950	28008	122944	94559
Auxiliary Mach. Req. Vol.	$feet^3$	44918	44892	45269	45518	45426	45642
Fuel Tankage Vol.	$feet^3$	28036	28221	29351	34653	31210	32432
Req. Duct Vol.	$feet^3$	12523	.9413	10223	3820	10866	15055
Total Machinery Volume	$feet^3$	205367	201632	216187	231878	298869	276010

[1] Includes 5000 kW Ship Service Power. [2] Includes 7500 kW Ship Service Power.

3.2.4.4 Solid Oxide Fuel Cell Variant Designs

The Solid Oxide fuel cell technology has not been defined to the same extent as the other types of fuel cells discussed in this study. For this reason, point designs were not completed for each variant for the Solid Oxide fuel cells.

An initial impact of the Solid Oxide fuel cell technology was discussed in the parametrics section. It is shown that the Solid Oxide is a promising technology which should be examined in more detail in the future.

3.2.4.5 DDG 51 Class Ship Service Power Backfit Variants

For the backfit variants, each of the Allison gas turbine generator sets was directly replaced with a 2500 kW fuel cell power plant. Since these are strictly backfit variants, no other aspect of the DDG 51 was allowed to change. The dimensions, structure, tankage volumes, and arrangements of the ship were held constant.

Three variant models were produced with the gas turbine generator sets being replaced in turn with Proton Exchange Membrane, Molten Carbonate, and Phosphoric Acid fuel cell power plants.

Due to the fact that the fuel cell power plants produce DC power and the DDG 51 ship service system is an AC system, an additional weight and volume had to be added to each fuel cell power plant to account for the necessary inverters. This will allow the fuel cell power plants to feed power into the same load banks as the original gas turbine generator sets. For the 2500 kW plants, these inverters contributed 8.27 LT and 36.0 ft^3.

The results for the fuel cell ship service power backfit variants of the DDG 51 baseline model are presented in Table 3-12.

Table 3-12

DDG 51 Ship Service Backfit Ship Impact Results

	Units	Baseline	PEM Fuel Cell	MC Fuel Cell	PA Fuel Cell
Displacement	LT	8311	8265	8442	8432
Length Between Perp.	feet	466	466	466	466
Propulsion Plant Weight	LT	789	789	789	789
Electric Plant Weight	LT	382	336	513	503
Total Fuel Weight	LT	1187	1187	1187	1187
Installed Prop. GT Power	kW	76913	76913	76913	76913
Installed SS GT Power	kW	7500	0	0	0
Installed Fuel Cell Power	kW	0	7536	7500	7500
Maximum Electric Load	kW	3644	3651	3651	3651
Maximum Speed	Kts	-	+0.0	-0.1	-0.1
Total Fuel Used - w/ M.P.	LT	13069	10645	10978	10683
Prop. Plant Req. Vol.	$feet^3$	155910	155908	155917	155916
Electric Plant Req. Vol.	$feet^3$	69184	57005	62722	61507
Auxiliary Mach. Req. Vol.	$feet^3$	57409	57404	57424	57423
Fuel Tankage Vol.	$feet^3$	50197	50197	50194	50197
Req. Duct Vol.	$feet^3$	49048	41766	41881	41881
Total Machinery Volume	$feet^3$	381748	362280	368138	366924

The most significant impact with a ship service backfit in a DDG 51 class destroyer is in the total fuel used when the destroyer is assumed to complete the same notional mission profile used in the other destroyer variants. The specific fuel consumption under various load conditions for each of the fuel cell types is less than that of the gas turbine generators. Fuel savings of 2424, 2091, and 2386 LT were manifest using the notional mission profile in variants powered by PEM, MC, and PA fuel cell types respectively. This impact can represent a significant savings in fuel costs over the lifetime of the ship when compared to the DDG 51 baseline. Assuming one time through the mission profile each year, over a 30 year life of the ship, the PEM fuel cell power plants will save approximately 23 million gallons of fuel.

Even though the MC and PA fuel cells have lower fuel consumption rates than the PEM fuel cell, they do not improve the overall fuel economy of the ship as much as the PEM fuel cells. This is due to their much larger plant weight and volume compared to the PEM fuel cells. Whereas the PEM fuel cells lead to a decrease in the electric plant (SWBS 300) weight of 46 LT, the MC and PA fuel cells increased the electric plant weight by 131 and 121 LT respectively. For the MC and PA fuel cell plants, this increase in electric plant weight, increased the displacement of the destroyer which led to an increase in the ship's resistance. This decreased the advantage that MC and PA fuel cells would have had with respect to the fuel used in the sole production of ship service power.

The change in displacement in the MC and PA fuel cell variants, also led to a slight change in ship speed. With the increase in resistance, the maximum speed of the destroyer was reduced by 0.1 knots.

An additional positive aspect of a fuel cell backfit on the DDG 51, is the reduced internal volume required by the machinery in the electric plant and the intake and exhaust ducts for the power plants. Within the original scheme of the backfit option, the internal structure of the ship is not changed so any backfit would just end up with extra volume within the ship which will not be used. However, if internal space is important enough at the time of the backfit, the reduction in the required volumes gives the designers the opportunity to redesign the internal spaces of the ship to make more efficient use of the space.

3.3 Corvette

3.3.1 Approach

This section discusses the impact of using fuel cell technology on a Corvette.

The approach used to evaluate fuel cells on the Corvette involved the establishment of two baseline ships that met certain design requirements and were optimized (by varying their overall dimensions) to achieve minimum displacement. While varying the dimensions, the principal hullform coefficients were held constant and, in each case, a balanced design was sought that satisfied the requirements.

The first baseline was equipped with four centralized diesel generators. The second baseline (referred to as the Distributed Baseline) was equipped with 14 diesel generators distributed through five independent zones. Both baselines have a CODOG propulsion system.

Various power plants were then replaced on each ship by fuel cell power plants. For each application, the same design requirements had to be met as in the baseline ships and minimum weight solutions found. The characteristics of the fuel cell variants were then compared against the corresponding baseline to evaluate the technology.

In addition to the variant designs, a series of minimum weight solutions were generated for each application for generic fuel cell plants of various weight-to-power ratios and SFCs. The displacement of these solutions were plotted versus the corresponding values of fuel cell plant weight-to-power and SFC. The results were used as a quick method of assessing the impact of fuel cell plant design.

Baselines and Variants Examined

Three power plant replacement scenarios were examined on the Corvette. These were:

- Direct replacement of all the ship service generators on the baseline
- Replacement of the CODOG propulsion system and ship service generators on the baseline with an integrated (fuel cell) electric drive configuration.
- Direct replacement of all the ship service generators on the distributed (ship service) baseline

The machinery suits used in the baseline and variants are shown in Table 3-13.

Table 3-13

Corvette Machinery Suites

Ship	Propulsion	Ship Service
Baseline	CODOG 1 Gas Turbine 2 Diesels	4 Diesel Generators (Includes 1 Emergency Ship Service Generator)
Ship Service Variants	CODOG 1 Gas Turbine 2 Diesels	4 Fuel Cell Plants (Includes 1 Emergency Ship Service Generator)
Propulsion Variants	2 or 4 Fuel Cell Plants 2 Permag Motors	Ship Service is Propulsion Derived + 1 fuel Cell Emergency SS Generator
Distributed Baseline	CODOG 1 Gas Turbine 2 Diesels	14 Diesel Generators (Distributed through 5 Independent Zones)
Distributed Ship Service Variants	CODOG 1 Gas Turbine 2 Diesels	14 Fuel Cell Plants (Distributed through 5 Independent Zones)

For each of the above variants, point designs were established for each of the four fuel cell types considered in this study. These were:

- Proton Exchange Membrane (PEM)
- Phosphoric Acid (PA)
- Molten Carbonate (MC)
- Solid Oxide (SO).

Design Requirements and Standards

As was mentioned earlier, the corvettes were designed to meet fixed requirements, margins and standards. These are summarized in Table 3-14.

The primary mission of the corvette was to provide a quick response to regional conflicts with an emphasis on anti-surface warfare. A more complete list of requirements, along with a projected tactical concept, is provided in Appendix C.

Table 3-14

Fixed Requirements for Corvette

Performance Maximum Speed Range/Endurance/Fuel	 27 kts 2000 nm at 27 kts 1000 nm at 12 kts 322 hours at loiter/anchor
Crew Complement	100
Military Payload SWBS 400 - Mission Electronics SWBS 700 - Armament Loads (F20) - Ammunitions	 43.7 LT 56.8 LT 37.5 LT
Material Hull Superstructure	 Steel Steel
Hullform L/B Hull Beam-to-Draft Ratio Maximum Block Coefficient	 8.5 3.0 0.48
Margins, Design Weight (Design and Construction) KG (Design and Construction) Accommodation Electric Plant (Design and Construction Propulsion Power Fuel	 10.0% of lightship weight (sum of SWBS 100 to 700) for contract, detail design and construction margin 10% of lightship KG for contract, detailed design and construction margin 10% 20% of maximum load 8% added to the calculated drag 10% for hull fouling and tailpipe allowance
Margins, Service-Life Weight KG Electric Plant	 10% of full-load weight (sum of SWBS 100 to 700) but performance to be adjusted 1 ft added to the full-load kg 20% of maximum load

As can be seen from Table 3-14, the hullform was held fairly constant, so improvements attributed to the incorporation of fuel cell technology could be better isolated.

3.3.2 Corvette Baselines

Two baselines were used in the corvette study to provide references for the ship impact assessment of fuel cells. These baselines are described as follows:

3.3.2.1 Corvette Baseline (Standard)

The Corvette baseline design was derived from an analysis of the trends in the state-of-the-art of combatant vessels in this size range. Details of this analysis are found in Appendix C.

The Corvette baseline was configured with a CODOG propulsion system containing one conventional LM2500 gas turbine rated at 26,250 hp and two 2700 hp diesels. The diesels power the ship at 17 kts and below.

In the corvette baseline, there are four diesel ship-service generators onboard rated at a nominal 400 kW each. One of the generators serves as a dedicated emergency/standby plant and is located in a forward compartment of the vessel. The electrical system of the ship was assumed to run on direct current with conversion to AC power locally as required. The displacement of the ship is 1996 LT.

A conceptual drawing of this baseline is shown in Figure C-1 in Appendix C.

3.3.2.2 Distributed Corvette Baseline

In the second corvette baseline, a conventional distributed ship-service system was created to allow a direct comparison of the fuel cell variants with distributed electrical systems. The distributed baseline contains 14 diesel generators rated at 121 kW distributed in five zones throughout the ship. Two electrical buses run through the ship, providing adequate redundancy. Switches are located on the buses at zone transition points along the length of the ship so power can be shared by different zones if required. The electrical system of the ship was assumed to run on direct current as in the first baseline. Dedicated fuel tanks exist for each zone. The displacement of the ship is 2033 LT.

3.3.3 Corvette Parametrics

As was discussed in Section 3.2.3 for the Destroyer, a parametric study was also run for the Corvette in which a generic fuel cell plant was assumed. Three parameters were varied. These were the Specific Fuel Consumption (SFC), weight-to-power ratio and plant density of the fuel cell plants in the ships. The volume of the fuel cell plants varied proportionally with weight for a given plant density and was, therefore, inherently addressed with the three parameters above.

It was found that plant density had only a second order effect on the trends. Since most of the plants studied had a density around 35 lb/ft^3, this value was retained as representative of the fuel cells studied. Further analysis of the influence of plant density was dropped.

It should be noted that the shape of the SFC curves for all fuel cell plants considered in the parametric study were assumed to be the same as that of a PEMFC plant. When ship designs were generated in more detail, this characteristic along with others, such as exhaust and intake sizes, were fine tuned. Keeping this in mind, the parametrics should be viewed as providing results applicable to first order designs to indicate approximate trends only.

Parametrics were generated for each of the three ship variants studied for the Corvette. The results are shown in Figures 3-4 through 3-6. The characteristics of the four fuel cell types examined are plotted in the figures. The displacement of the corresponding baseline ship is also shown in all of the plots for comparison.

Figure 3-4 shows a carpet plot of the propulsion variants of the Corvette. It can immediately be seen that the use of MCFC plants result in a variant which has a displacement approximately 500 LT greater than the displacement of the baseline. The displacement of the PAFC powered variant is about 250 LT greater than the displacement of the baseline. The PEMFC and SOFC (planar) powered variants weigh about 300 LT less than the baseline.

It can also be seen in Figure 3-4 that even if the MCFC variant achieved a very low SFC of say 0.3 lb/kW-hr, the variant would still weigh more than the baseline. It could be deduced that MCFC developers should concentrate on reducing the weight of MCFC plants to around 20 lb/kW in order for MCFC plants to become competitive for propulsion applications.

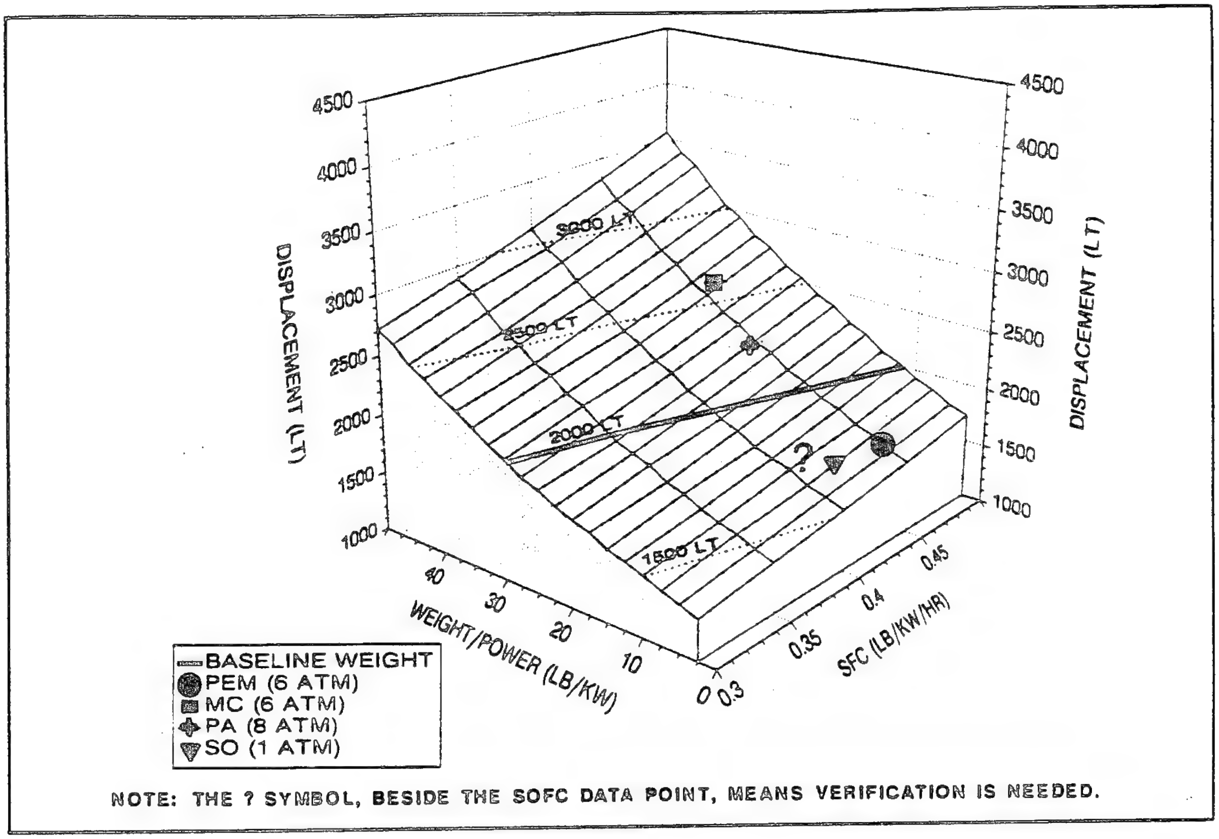


Figure 3-4. Propulsion Variants, Corvette

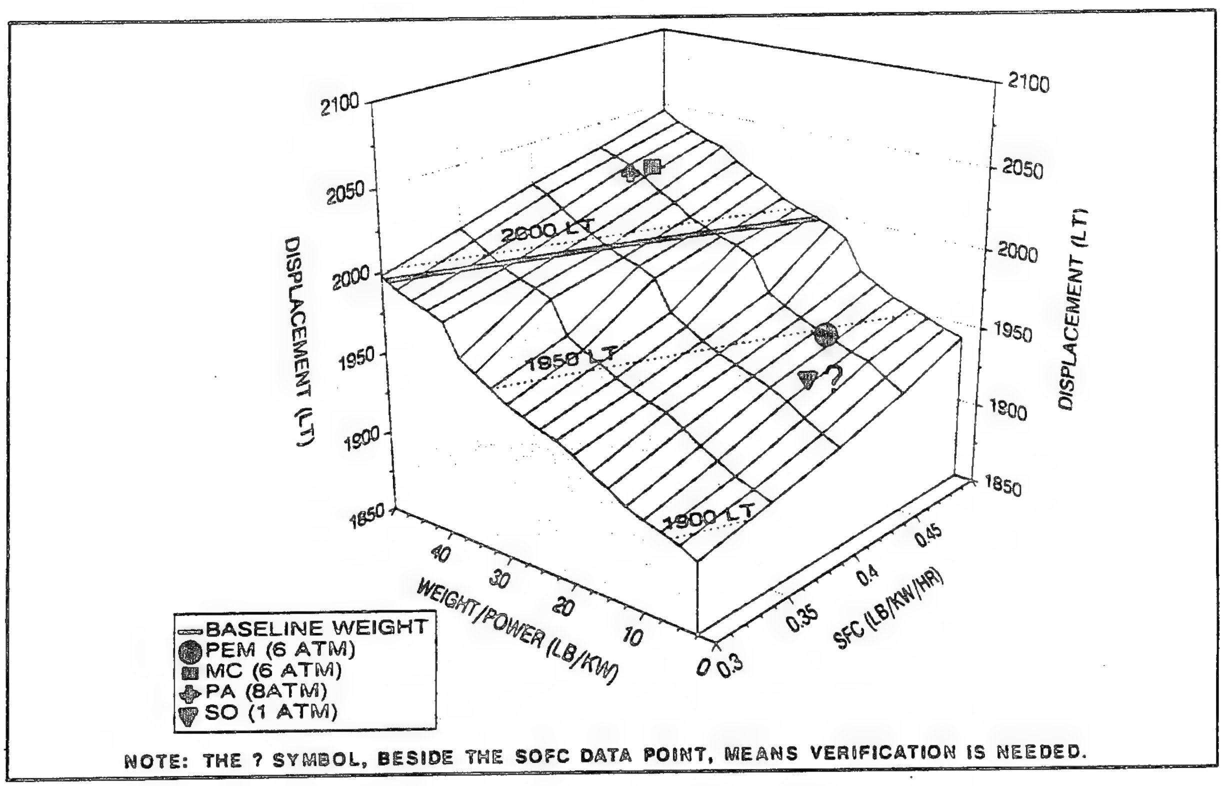


Figure 3-5. Ship Service Variants, Corvette

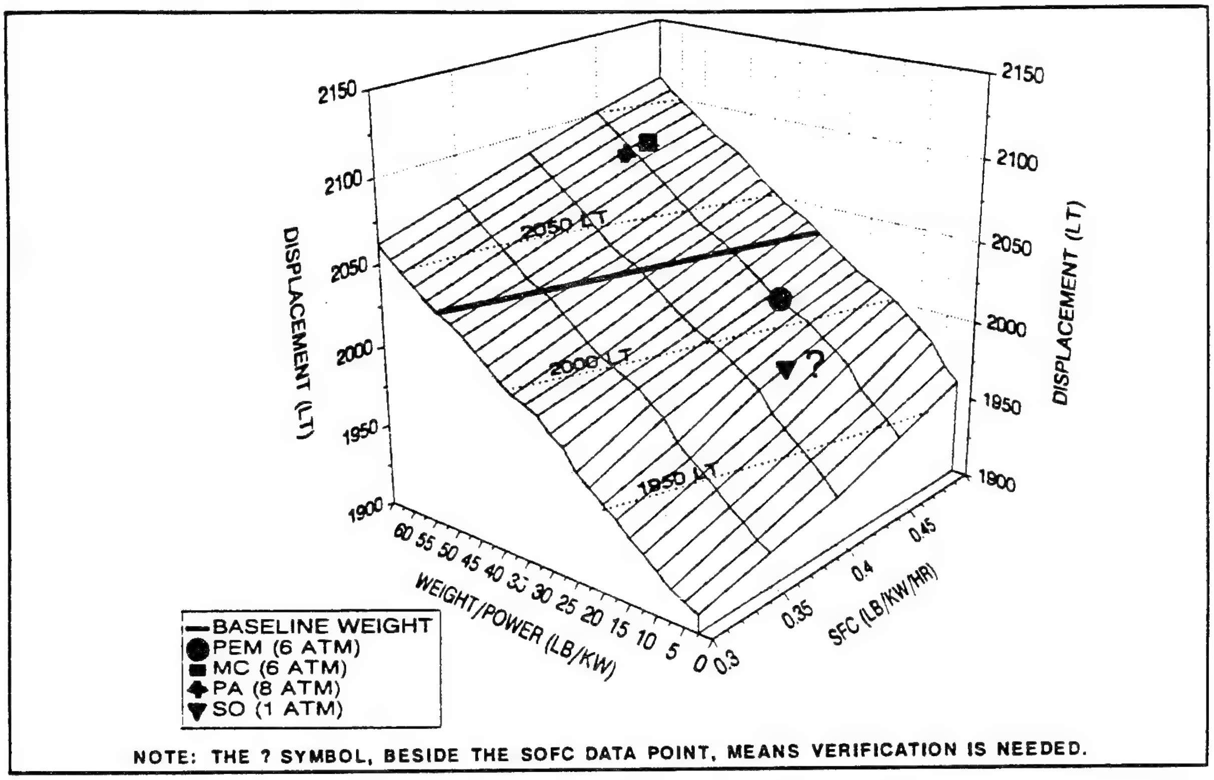


Figure 3-6. Distributed Ship Service Variants, Corvette

In Figures 3-5 and 3-6 the carpet plots for the ship service variants show similar trends as those seen for the propulsion variants but to a much lesser degree.

It should be noted that the question mark beside the SOFC (planar) data points in Figures 3-4 through 3-6 signifies that there is a lesser degree of confidence in the data that characterizes the plant. Further verification of the data is needed.

When compared to the results of the parametric analysis for the Destroyer, it is found that fuel cells can more easily benefit the Corvette because of the advanced features that the Destroyer baseline already has. However, similar trends were found in both studies, especially regarding the relative influence of each parameter.

3.3.4 Corvette Point Designs Study

The specific characteristics of each fuel cell type was incorporated into the design synthesis model used in this study for the Corvette design. Point designs were developed for each application and each fuel cell type. The principal results and findings are provided in this section.

3.3.4.1 Proton Exchange Membrane (PEM) Variants

Ship designs using PEMFC power plants were generated for the three applications studied. Table 3-15 shows a summary of the characteristics of the variants generated along with the characteristics of their corresponding conventional baselines. The range calculated in the table is based on the speed/percent time profile shown in Table 3-16 and does not assume the four month deployment time, but the time to burn all useable fuel onboard (90% of total fuel). The amount of fuel used with the mission profile (W/MP), shown in Table 3-15, is based on a four month deployment time. The duct volume is taken to be that volume of ducting that exists outside of the engine room.

Table 3-15

Comparison of Baseline Ships With Ships Having PEM Fuel Cells, Corvette

	Units	Baseline	Ship Service Variant	Propulsion Variant	Distributed Baseline	Distributed Ship Service Variant
Displacement	LT	1,986	1,948	1,690	2033	2,009
Length Between Perps	FT	315	312	297	318	312
SWBS 200 Weight	LT	215	214	159	215	214
SWBS 300 Weight	LT	51	44	30	56	44
Total Fuel Weight	LT	410	401	356	411	401
Installed Prop GT Power	kW	19,569	19,569	0	19,569	19,569
Installed Prop Diesel Pwr	kW	3,907	3,872	0	3,920	3,906
Installed SS Diesel Power	kW	1,599	0	0	1,686	0
Installed Fuel Cell Power	kW	0	1,582	20,927[1]	0	1,687
Maximum Electric Load	kW	833	824	786	841	837
Max. Ship Spd at Full Load	KTS	27.0	27.0	27.0	27.0	27.0
Actual Range - W/MP, W/Fuel on Ship	NM	5,095	5,063	4,981	5,096	5,097
Fuel Used W/MP (4 Month Mission)	LT	3,348	3,296	2,979	3,356	3,319
SWBS 200 Reqd Volume	FT^3	43,872	43,400	31,480	44,344	44,104
SWBS 300 Reqd Volume	FT^3	14,720	11,392	6,920	26,080	19,272
SWBS 500 Reqd Volume	FT^3	50,336	49,288	42,768	50,960	50,312
Fuel Tankage Volume	FT^3	17,539	17,154	15,229	17,589	17,324
Required Duct Volume	FT^3	7,480	6,912	288	7,584	6,928
Total Machinery Volume	FT^3	133,947	128,146	96,685	146,557	137,940

[1] Includes 1509 kW ship service power.

Table 3-16

Corvette Mission Profile

	Speed (kts)	Percent Time	Time (hrs)
Anchor	0	5	144
Low Speed on Diesels	12	30	864
Top Speed on Diesels	17	50	1440
Maximum Sustained on Gas Turbine	26	10	288
Top Speed on Gas Turbine	27	5	144
Total/Average	16.05	100	2880

PEM Ship Service Variant

This ship service variant was configured in the same manner as the baseline. However, four fuel cell power plants were used to supply ship service power instead of four diesel generators. As was mentioned for the baseline, one of the generators serves as a dedicated emergency plant. Since the fuel cells produce direct current, no power conditioning equipment was included with the plants.

The ship was then optimized by taking advantage of the weight, volume and fuel savings associated with the PEM plants. The dimensions of the ship were allowed to change while keeping the basic hullform the

same and a minimum displacement solution was chosen. The design requirements of the baseline ship were used.

As can be see in Table 3-15, the ship service variant weighs about 40 LT less and is about 3 ft shorter than the baseline. The duct volume has decreased 568 ft^3 and the total machinery volume has decreased by 5801 ft^3. The fuel economy improved and yielded a 52 LT (~16,600 gal) saving in a four month mission.

Drawings of this variant can be found in Appendix C, Figure C-2.

PEM Propulsion Variant

The machinery arrangement in the propulsion variants greatly differed from that used in the Corvette baseline. Instead of a CODOG propulsion system, an integrated electric drive system was used. Two and in some cases four, large fuel cell plants (depending upon the fuel cell type) were arranged to supply power to two permanent magnet motors driving two propellers directly. The fuel cell plants also supply ship service-power for the ship. The plants are located in separate watertight compartments to provide better survivability characteristics. A small dedicated emergency generator, located in a forward compartment of the ship, was also included in the arrangement.

The PEM variant having fuel cell powered main propulsion was developed by replacing the CODOG propulsion system on the baseline by two PEMFC plants which supply power to two permanent magnet motors which, in turn, drive the propellers. The ship service power is also supplied by the two PEMFC propulsion plants (as an integrated system). A third PEMFC plant is included in the configuration as an emergency generator for ship service power. This variant was also optimized for minimum displacement.

The arrangement drawings for this variant are included in Appendix C, Figure C-3. The drawings dramatically illustrate the absence of the massive vertical exhaust stacks found in the baseline (also see Figure 1-3). The exhaust has, instead, been vented out the side of the ship. This is made possible by a lower exhaust flow rate, lower exhaust temperature and a virtual elimination of pollutants in the exhaust gas (cleaner, cooler exhaust allows venting near manned spaces).

From Table 3-15 it can be seen that the displacement of the propulsion variant is 306 LT less than the baseline and that the length is 18 ft less than the baseline. It can also be seen that massive weight and volume savings in SWBS groups 200 and 300 along with duct volume reduction have contributed significantly to the overall reduction in ship size. The fuel economy of the ship has also improved significantly as seen by the 369 LT (118,000 gal) of fuel saved over a four month mission.

PEM Distributed Ship Service Variant

The distributed ship service variants were similar in arrangement as the distributed baseline. Fourteen fuel cell plants were distributed in five zones of the ship. The nominal plant sizes are approximately 120 kW each. The number of plants used in each zone of the ship was dictated by the associated power requirements of the zones. Two power buses (for redundancy) ran the length of the ship and contain switches at zonal transition points to allow zones to share power if needed. Dedicated fuel tanks (day tanks) were assumed for each zone. A more detailed discussion of the approach is provided in Appendix C.

The distributed ship service variant was developed by replacing the 14 diesel generators on the baseline by 14 x 120 kW PEM power plants distributed into five zones throughout the ship. The ship was allowed to be optimized to minimize displacement while meeting the design requirements. The zones are electrically interconnected for redundancy and the exhaust of the fuel cell electric generators is vented out the side of the ship.

As can seen in Table 3-15, the distributed ship-service variant weighs about 24 LT less than the distributed baseline. The electrical system (SWBS 300) and duct volume have significantly decreased by 6808 ft^3 and

656 ft^3, respectively. It can also be seen that some fuel savings are present. Drawings for this variant can be found in Appendix C, Figure C-4.

3.3.4.2 Molten Carbonate (MC) Variants

Detailed ship designs were generated using MCFC power plants in the three applications studied. Table 3-17 shows a summary of the characteristics of the variants generated.

Table 3-17

Comparison of Baseline Ships With Ships Having MC Fuel Cells, Corvette

	Units	Baseline	Ship Service Variant	Propulsion Variant	Distributed Baseline	Distributed Ship Service Variant
Displacement	LT	1,996	2,068	2,789	2033	2,097
Length Between Perps	FT	315	318	354.3	318	320
SWBS 200 Weight	LT	215	218	500	215	219
SWBS 300 Weight	LT	51	68	55	56	84
Total Fuel Weight	LT	410	431	510	411	421
Installed Prop GT Power	kW	19,569	19,570	0	19,569	19,570
Installed Prop Diesel Pwr	kW	3,907	3,978	0	3,920	4,012
Installed SS Diesel Power	kW	1,599	0	0	1,696	0
Installed Fuel Cell Power	kW	0	1,616	25,902[1]	0	1,706
Maximum Electric Load	kW	833	842	953	841	846
Max. Ship Spd at Full Load	KTS	27.0	26.8	27.0	27.0	26.8
Actual Range - W/MP, W/Fuel on Ship	NM	5,095	5,182	4,753	5,096	5,148
Fuel Used W/MP (4 Month Mission)	LT	3,348	3,461	4,464	3,356	3,403
SWBS 200 Reqd Volume	FT^3	43,872	44,376	60,200	44,344	44,624
SWBS 300 Reqd Volume	FT^3	14,720	16,896	12,408	26,080	27,456
SWBS 500 Reqd Volume	FT^3	50,336	51,520	62,168	50,960	51,888
Fuel Tankage Volume	FT^3	17,539	18,437	21,817	17,589	18,009
Required Duct Volume	FT^3	7,480	6,944	400	7,584	6,960
Total Machinery Volume	FT^3	133,947	138,173	156,993	146,557	148,937

[1]Includes 1830 kW ship service power.

MC Ship Service Variant

From Table 3-17 it can be seen that the MC ship-service variant weighs 72 LT more, and is 3 ft longer, than the baseline. The reason for the increased ship size and weight appears to be due to a weight increase in the SWBS 300 group. The increased weight also results in increased drag and fuel consumption which offset the low fuel consumption of the fuel cell electric plant. It was found that the duct volume is less than that in the baseline even though the maximum electric load is up slightly.

MC Propulsion Variant

In Table 3-17 it can be seen that the MC propulsion variant is 793 LT heavier than the baseline ship; a 40% increase. This increase is due, in large part, to an increase in propulsion machinery weight. It should also be noted that four MCFC plants are supplying propulsion power in this variant. This number of plants was found to be more optimum as the SFC profile of the MCFC plants was unfavorable at low power. Thus, it is possible to run only two out of four plants to achieve a better fuel efficiency at low speeds.

However, the practicality of this scenario is tied to a quick start-up of the plants which has been identified as a potential problem for this type of plant (due to its high operating temperature).

MC Distributed Ship-Service Variant

Similar trends as shown for the centralized ship service application are seen for the distributed ship service application. It can be seen in Table 3-17 that the displacement for this MCFC variant is 64 LT greater than the distributed baseline.

3.3.4.3 Phosphoric Acid Variants

Detailed ship designs were generated using PAFC power plants in the three applications studied. Table 3-18 shows a summary of the characteristics of the variants generated.

Table 3-18

Comparison of Baseline Ships With Ships Having PA Fuel Cells, Corvette

	Units	Baseline	Ship Service Variant	Propulsion Variant	Distributed Baseline	Distributed Ship Service Variant
Displacement	LT	1,996	2,043	2,503	2033	2,052
Length Between Perps	FT	315	316.6	356.1	318	318.2
SWBS 200 Weight	LT	215	217	382	215	217
SWBS 300 Weight	LT	51	61	48	56	70
Total Fuel Weight	LT	410	428	464	411	414
Installed Prop GT Power	kW	19,569	19,570	0	19,569	19,570
Installed Prop Diesel Pwr	kW	3,907	3,959	0	3,920	3,957
Installed SS Diesel Power	kW	1,599	0	0	1,696	0
Installed Fuel Cell Power	kW	0	1,607	24,008[1]	0	1,697
Maximum Electric Load	kW	833	837	925	841	842
Max. Ship Spd at Full Load	KTS	27.0	26.9	27.0	27.0	26.9
Actual Range - W/MP, W/Fuel on Ship	NM	5,095	5,173	4,759	5,096	5,123
Fuel Used (W/MP (4 Month Mission)	LT	3,348	3,442	4,060	3,356	3,366
SWBS 200 Reqd Volume	FT^3	43,872	44,136	57,760	44,344	44,360
SWBS 300 Reqd Volume	FT^3	14,720	15,272	10,920	26,080	23,408
SWBS 500 Reqd Volume	FT^3	50,336	51,072	57,000	50,960	51,088
Fuel Tankage Volume	FT^3	17,539	18,309	19,849	17,589	17,710
Required Duct Volume	FT^3	7,480	6,920	336	7,584	6,912
Total Machinery Volume	FT^3	133,947	135,709	145,865	146,557	143,478

[1]Includes 1776 kW ship service power.

PA Ship Service Variant

In Table 3-18 it can be seen that the PAFC ship service variant weighs 47 LT more than the baseline ship. The duct volume for the machinery has decreased over the baseline but the overall machinery volume has increased by almost 2000 ft^3. The fuel economy of the variant is slightly worse than the baseline, using 94 LT more fuel over a four-month mission.

PA Propulsion Variant

It can be seen in Table 3-18 that the PAFC propulsion variant weighs 507 LT more than the baseline. It should be noted that four fuel cell plants, at ~6000 kW each, are used to supply propulsion and electric power instead of two plants as in the PEMFC propulsion variant. The fuel economy of the variant is poor compared to the baseline. The variant burns 712 LT more (21% more) fuel than the baseline over a four-month mission. It can also be seen that the powering requirement of this variant is greater than the baseline and requires more machinery space.

PA Distributed Ship Service Variant

From Table 3-18 it can be seen that the distributed ship service variant with PAFC power plants is 19 LT heavier than the distributed baseline with diesel electric generators. It should be noted that the total machinery volume has decreased by about 3000 ft^3 even though the electrical system weight (SWBS 300) is up by 14 LT. Fuel economy is about the same as the baseline.

3.3.4.4 Solid Oxide Variants

Detailed ship designs were generated using SOFC power plants in the three applications studied. Table 3-19 shows a summary of the characteristics of the variants generated.

Table 3-19

Comparison of Baseline Ships With Ships Having SO Fuel Cells, Corvette

	Units	Baseline	Ship Service Variant	Propulsion Variant	Distributed Baseline	Distributed Ship Service Variant
Displacement	LT	1,996	1,914	1,606	2033	1,977
Length Between Perps	FT	315	310	295	318	315
SWBS 200 Weight	LT	215	213	163	215	214
SWBS 300 Weight	LT	51	41	28	56	50
Total Fuel Weight	LT	410	385	291	411	394
Installed Prop GT Power	kW	19,569	19,570	0	19,569	19,570
Installed Prop Diesel Pwr	kW	3,907	3,844	0	3,920	3,878
Installed SS Diesel Power	kW	1,599	0	0	1,696	0
Installed Fuel Cell Power	kW	0	1,573	20,009[1]	0	1,678
Maximum Electric Load	kW	833	819	782	841	832
Max. Ship Spd at Full Load	KTS	27.0	27.1	27.0	27.0	27.06
Actual Range - W/MP, W/Fuel on Ship	NM	5,095	4,999	5,699	5,096	5,033
Fuel Used W/MP (4 Month Mission)	LT	3,348	3,208	2,125	3,356	3,260
SWBS 200 Reqd Volume	FT^3	43,872	43,152	35,088	44,344	43,856
SWBS 300 Reqd Volume	FT^3	14,720	11,952	6,832	26,080	20,464
SWBS 500 Reqd Volume	FT^3	50,336	48,592	40,752	50,960	49,688
Fuel Tankage Volume	FT^3	17,539	16,469	12,448	17,589	16,854
Required Duct Volume	FT^3	7,480	6,904	248	7,584	6,920
Total Machinery Volume	FT^3	133,947	127,069	95,368	146,557	137,782

[1]Includes 1501 kW ship service power.

SO Ship Service Variant

In Table 3-19 it can be seen that the ship service variant in which SOFC electrical generators are used, weighs 82 LT less than the baseline. The fuel economy of this variant allows it to burn 140 LT less fuel over a four-month mission. The total machinery volume of the variant is about 7000 ft^3 less than that of the baseline.

SO Propulsion Variant

In Table 3-19 it can be seen that the SOFC propulsion variant weighs 390 LT less than the baseline. The length of the variant has decreased by about 20 ft and the machinery volume has been reduced by almost 40,000 ft^3. Over a four-month mission, the variant consumes about 1223 LT less fuel than does the baseline. This equates to a 36% reduction in fuel usage.

SO Distributed Ship Service Variant

From Table 3-19 it can be seen that the distributed ship service variant in which SOFC generators are used, weighs 56 LT less than the distributed baseline. For that matter, the distributed variant weighs less than the baseline with centralized ship service generators. Thus, it can be deduced that the use of the SOFC plants has offset the weight penalties associated with a distributed electrical system. Fuel economy has also improved over both baselines as seen by the amount of fuel used in a four-month mission.

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CHAPTER 4

MILITARY EFFECTIVENESS/COST

4.1 Introduction

While the previous chapter dealt with the physical impact of incorporating fuel cell power plants into the ship being studied, this chapter analyzes the effect on ship performance, effectiveness and cost that incorporation of the technology will bring about. Military effectiveness attributes of the fuel-cell ship variants are compared against those of the baseline ships. Environmental qualities are also examined because of their increasing importance in the global picture. Both acquisition and life-cycle cost are also addressed in this chapter.

The favorable or unfavorable effects of using the various fuel-cell technologies for the applications investigated are shown in the Executive Summary at the beginning of this report. The summary is based on the findings of this present chapter.

It should be noted that most of the assessment effort was performed on ship variants having PEMFC plants. Ships with MCFC and PAFC plants were not examined in detail since, in general, the ship impact of these plants is not favorable at this stage in their development for the scenarios studied. It should be mentioned, however, that the MCFC and PAFC plants did show some merit in the backfit of SS GT generators on the DDG 51. Ships with SOFC plants were also not assessed in detail since the data available on these plants needs further verification. However, it seems that the projected performance of the SOFC plants may surpass that of the PEMFC plants and it could be concluded that similar or better military effectiveness characteristics would also ensue.

4.2 Military Effectiveness

4.2.1 Mobility

4.2.1.1 Range

The operational range of each ship variant was examined to see how fuel cell technology affected this aspect of mobility. Of course, all ship variants were designed to meet the same range/endurance requirement and the fuel tanks, in each case, were sized accordingly. Thus, it can be deduced that all of the variants had near equivalent design range. This chapter looks a little deeper, however, at optional mission profiles.

The two types of mission profiles examined included: (1) the profiles defined in the ship-impact chapter which include anchor time and (2) constant speed missions in which all of the useable fuel onboard is consumed.

It should be noted that this present chapter provides a summary of significant findings and that a more detailed discussion, along with figures, is included in Appendix E under the subject of "Mobility, Range Assessment".

It was found that the PEMFC variants of the Corvette had range characteristics which were comparable to the baselines. The most significant finding was that the PEMFC propulsion variant was able to achieve similar range to that of the baseline in its gas turbine operating mode (18 kts and above) while having 10% less fuel onboard. In the diesel operating mode (17 kts and below) of the baseline, the PEMFC propulsion variant had comparable fuel consumption rates and would require an equivalent fuel capacity to achieve the same range. Using the mission profile that covers the whole speed range, including anchor time, the

PEMFC propulsion variant achieved an almost comparable range with the baseline while using 10% less fuel.

For the Destroyer, it was found that the overall fuel consumption rate for the PEMFC propulsion variant was about 5% less than that of the ICR GT driven baseline across the upper one-third of the operating speed range. The fuel capacity of the PEMFC propulsion variant was about 5% less. Thus, for each speed, comparable range was achieved. However, when a combined speed profile was used in which very low ship speeds and electrical loads at anchor are considered, the PEMFC propulsion variant achieved a range that was 14% greater than that of the baseline while having about 5% less fuel onboard. A large part of the improved fuel economy was due to the replacement of the less efficient standby generator (gas turbine) that is on the baseline Destroyer. An 8% increase in range could be attributed to all of the PEM variants as a result of replacing the standby generator alone.

The replacement of the gas turbine ship service generator set on the DDG-51 baseline by PEMFC plants proved to yield the most significant improvement in range. About a 25% increase in range was realized for the mission profile that included various speeds. When ranges at individual speeds were examined, it could be readily seen that at lower power levels the PEMFC plants were significantly out performing the conventional gas turbines in fuel economy. This signifies better SFC characteristics at low power levels for the PEM plants.

4.2.1.2 Habitability

Motions (Seakeeping)

A key issue in early stage ship design is the determination of seakeeping performance and operability. A method based on form coefficients was proposed by W.B. Wilson (Reference 10) using the Bales factor. This method was used to provide an initial assessment of the impact on seakeeping of the fuel cell variants.

The results showed that variations in operability index (percentage of time when the ship is fully operational in the North Atlantic) would not exceed 1% between the baselines and variants.

The largest negative impact was found for the propulsion PEMFC variant due to its reduced length and displacement. On the other hand, the MCFC and PAFC propulsion variants had improved seakeeping due to their increased length and displacement. Similar results were found for the Corvette and the Destroyer.

Seakeeping does not appear, therefore, as a critical issue regarding the use of fuel cells.

Airborne Noise

OSHA requires that human exposure to sound should not exceed 90 DBA for eight hours of exposure. Discomfort and hearing loss can occur at higher sound levels. The human ear is noticeably more sensitive to sound at frequencies between ~1000 and ~6000 Hz.

Sound levels from machinery can be reduced to acceptable levels by design. For exhaust, the location and orientation of the exhaust pipe in relation to habitable spaces plays a big factor in silencing requirements. When exhaust is vented far away from habitable spaces, silencing requirements diminish. Silencing usually has a performance penalty associated with it due to increased exhaust back pressure created by the damping material in the exhaust line.

Figure 4-1 shows sound levels of various unsilenced machinery ("A" weighted scale not used). It should be noted that the sound level scale is logarithmic and a 3 dB increase can represent a doubling in intensity. The figure is presented to give the reader a feel for the sound levels associated with various equipment. It can be seen that, for the smaller gas turbines, sound levels can be extremely high in the sensitive range of hearing. Diesel generators, in the power ranges shown, do not require a tremendous amount of silencing. For fuel-cell power plants, the amount of moving parts are much less than for equivalent diesel

or gas turbine plants, and explosive reactions are not occurring. For these reasons, sound levels should be less than for conventional plants. However, air compressors, fuel and water pumps are required for fuel cell plants, thus a certain amount of noise will be present. Noise levels of centrifugal fans that might be expected to be used for ventilation are shown in Figure 4-1. If it is considered that most of the fuel-cell plants studied are pressurized to 6 atmospheres and above, it can be surmised that turbo-compressors will be required to move air and fuel through the plants. It has been calculated that for a 20 MW plant, a turbo-compressor operating at a power level of about 3500 hp is required. If it is considered that the 4000 hp gas turbine shown in the plot is as loud as the required turbo-compressor, it can be deduced that the 20 MW (~27,000 hp) FC plant is still significantly quieter than a comparable sized gas turbine. Also, the silencing of a small part of the plant (the compressor in a fuel cell plant) is easier to achieve than it is for an entire gas turbine.

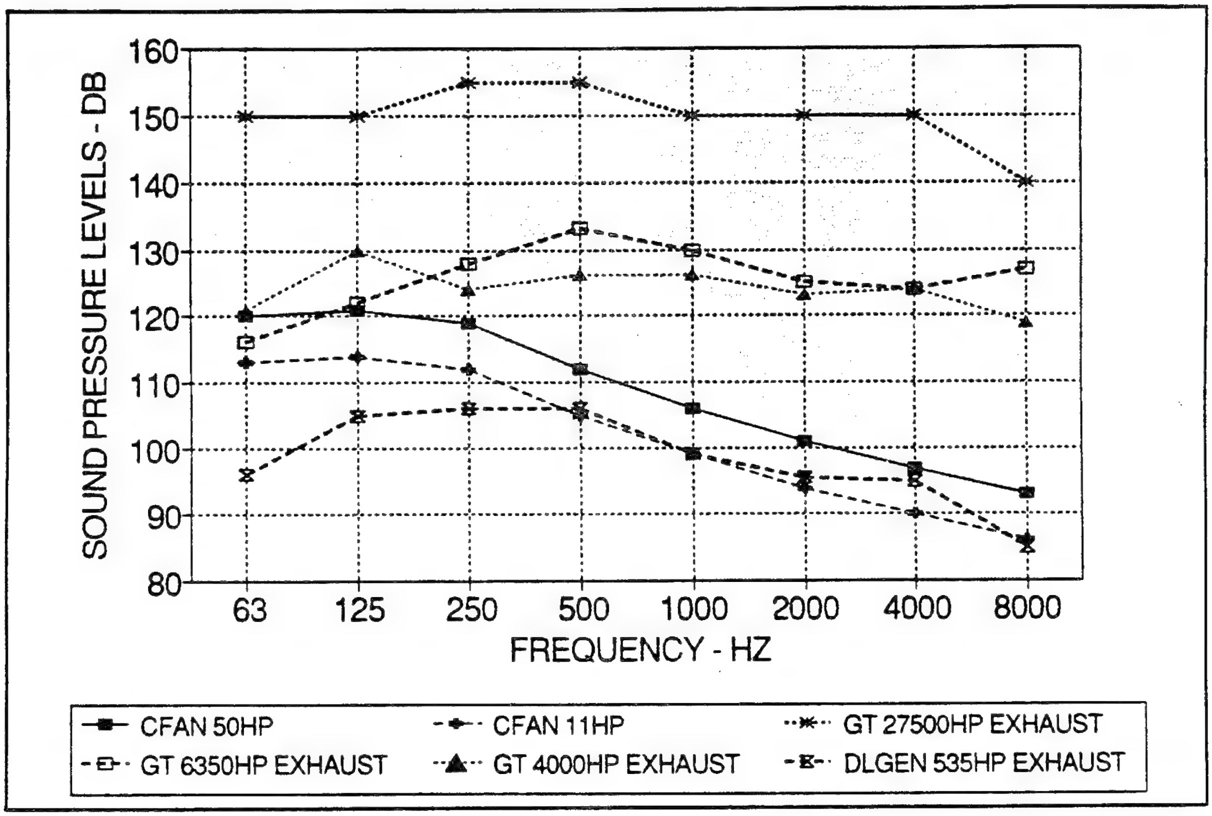

Figure 4-1. Sound Level of Machinery (Unsilenced)

4.2.1.3 Maneuverability

Tactical Turn Radius

The turn radii of the baselines and PEM variants were calculated based on empirical data relating non-dimensional turn radius to Froude Number.

Figure 4-2 shows the turn radii calculated for the Corvette baseline and variants for two ship speeds. It can be seen that the only noticeable improvement is in the propulsion variant at lower speeds. This is due to the shorter length of this variant compared to the baselines and the other variants.

In Figure 4-3, the turn radii of the Destroyer baseline and variants are shown. It can be seen that little change is realized by any of the variants.

No results are shown for the DDG-51 since the hullform was the same for the baseline and ship service variant.

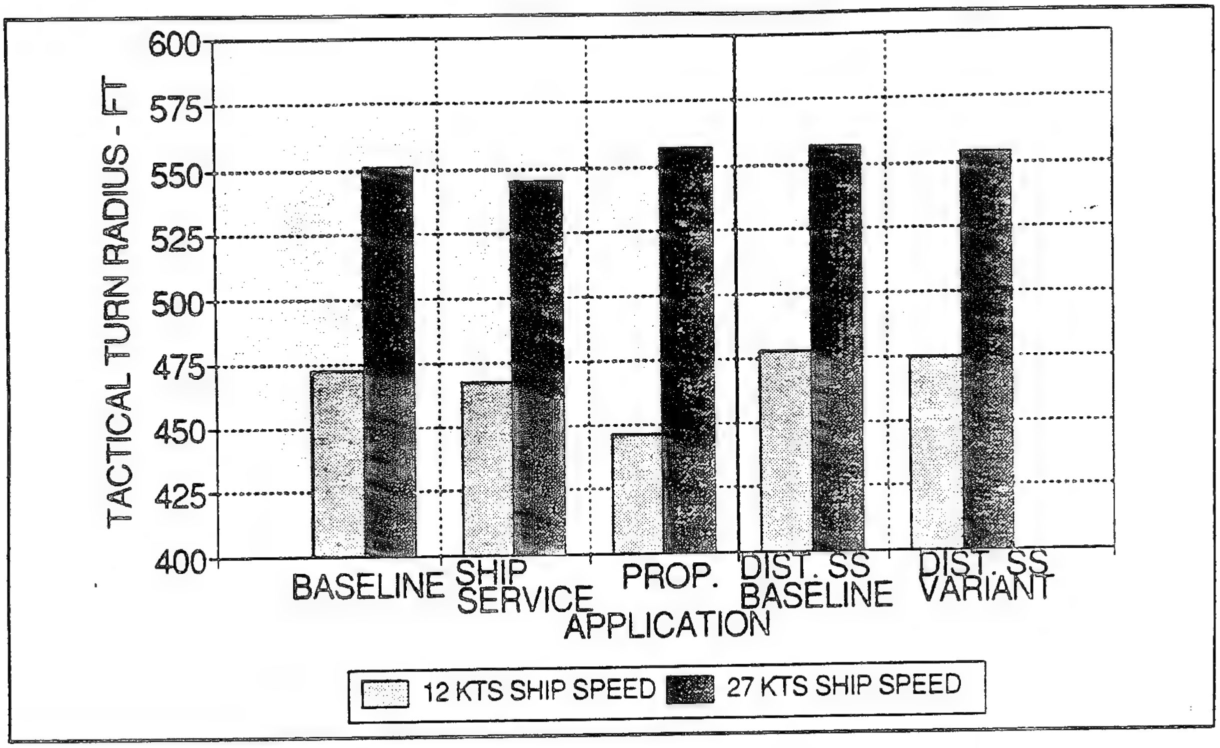

Figure 4-2. Tactical Turn Radius - Baselines and PEM Fuel Cell Variants - Corvette

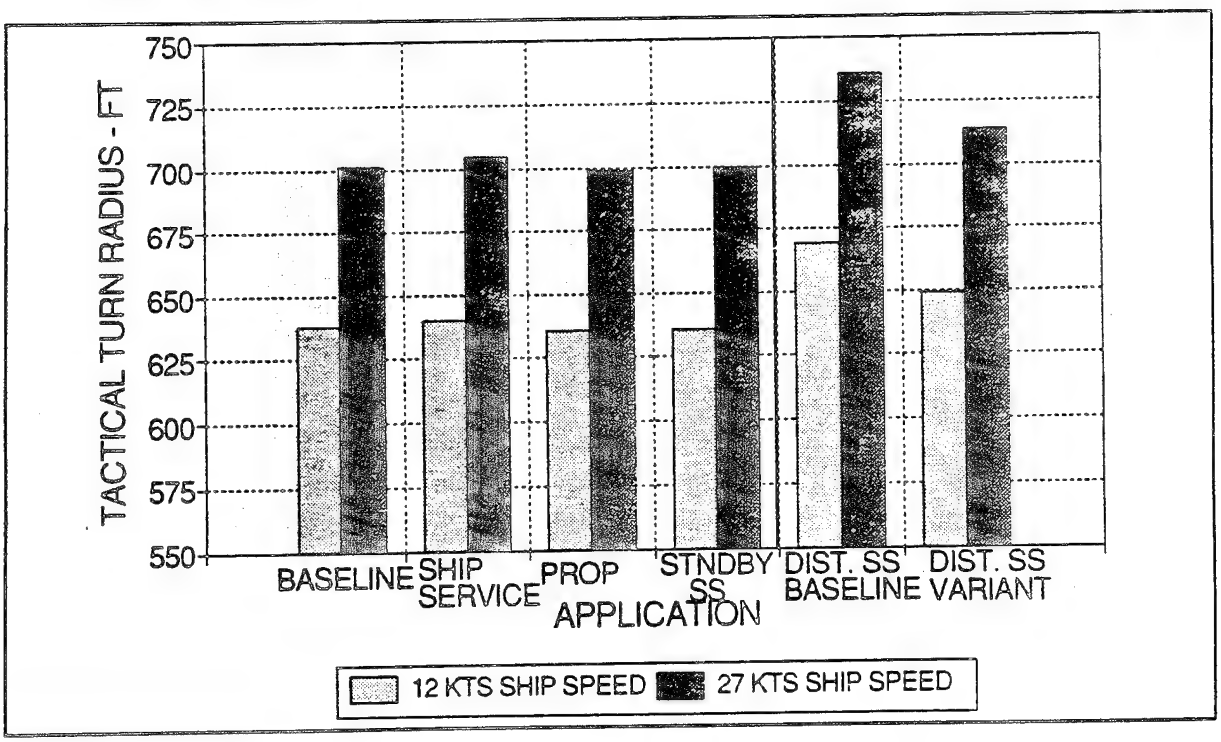

Figure 4-3. Tactical Turn Radius - Baselines and PEM Fuel Cell Variants - Destroyer

Start-Up Time

The start-up time from "cold iron" is shown in Table 4-1 for the various power plants being studied.

Table 4-1

Start-Up Time of Conventional and Fuel Cell Power Plants

	Preheated		Cold	
Plant Type	Hours	Minutes	Hours	Minutes
Diesel		0.5		5
Gas Turbine		1		5
PEMFC		*	1-2	
MCFC		*	12	
PAFC		*	5	
SOFC		*	8	
*If at or near operating temperature, start-up time should be a few minutes or less.				

Diesels can be started in cold conditions without preheated lube oil if need be. The result is increased smoke in the exhaust.

Gas turbines can also be started rapidly. Usually, a prestart checklist is required to be followed for military systems and is dependent on the auxiliaries associated with each system. Going through the checklist and bringing auxiliaries on-line can take up to a half hour. However, in emergency situations, much of the procedure can be bypassed. Thus, start-up times can vary depending on the application. For extremely cold starts, it is recommended that small amounts of start-up fuel be preheated to prevent waxing.

The start-up time for fuel-cell plants is largely dependent on operating temperature. Rapid heating rates can cause localized thermal stressing which may weaken or crack the cells (for this reason, repeated fast starts can shorten plant life). Thus, long start-up times are recommended to allow for uniform heating of the cells. Since the PEM fuel cell operates at the lowest temperature of the fuel-cell types examined (~200 degrees Fahrenheit), it has one of the quickest start-up times from cold, as seen in Table 4-1. The molten carbonate and solid oxide plants have the highest operating temperatures (1000+ degrees Fahrenheit) and, therefore, these plants require the lengthiest start-up times, also seen in Table 4-1. It should be noted that some SOFC plant designers claim that a 2-hour start-up time from cold iron is possible.

Another driver for the start-up time is the time it takes to attain a continuous reforming of the fuel. This aspect may be circumvented by incorporating a reserve of reformed fuel to be used during a starting cycle and to replenish it at the time of shut down.

In a battle scenario, if the fuel cell plants had to be temporarily shut-down, rapid restart times could be accomplished since latent heat would exist in the system.

Nonetheless, a long start-up time in cold conditions is a drawback of fuel-cell plants, and would hinder the mobility of the ship to a noticeable degree. A solution to the long start-up time is that a heater of some sort be run during down time for each plant.

Coasting Distance

An analysis of the coasting distance of the PEM variants was made. The analysis examines the distance required for a ship to stop while letting its propeller windmill. The results show how the different hulls of the variants perform in this aspect of maneuverability.

Figure 4-4 shows the coasting distance of the Corvette baseline and PEM variants. It can be seen that for all but the propulsion variant, there is practically no difference in coasting distance. The propulsion variant can stop at a distance ~300 ft shorter than the baseline from a maximum speed of 27 knots.

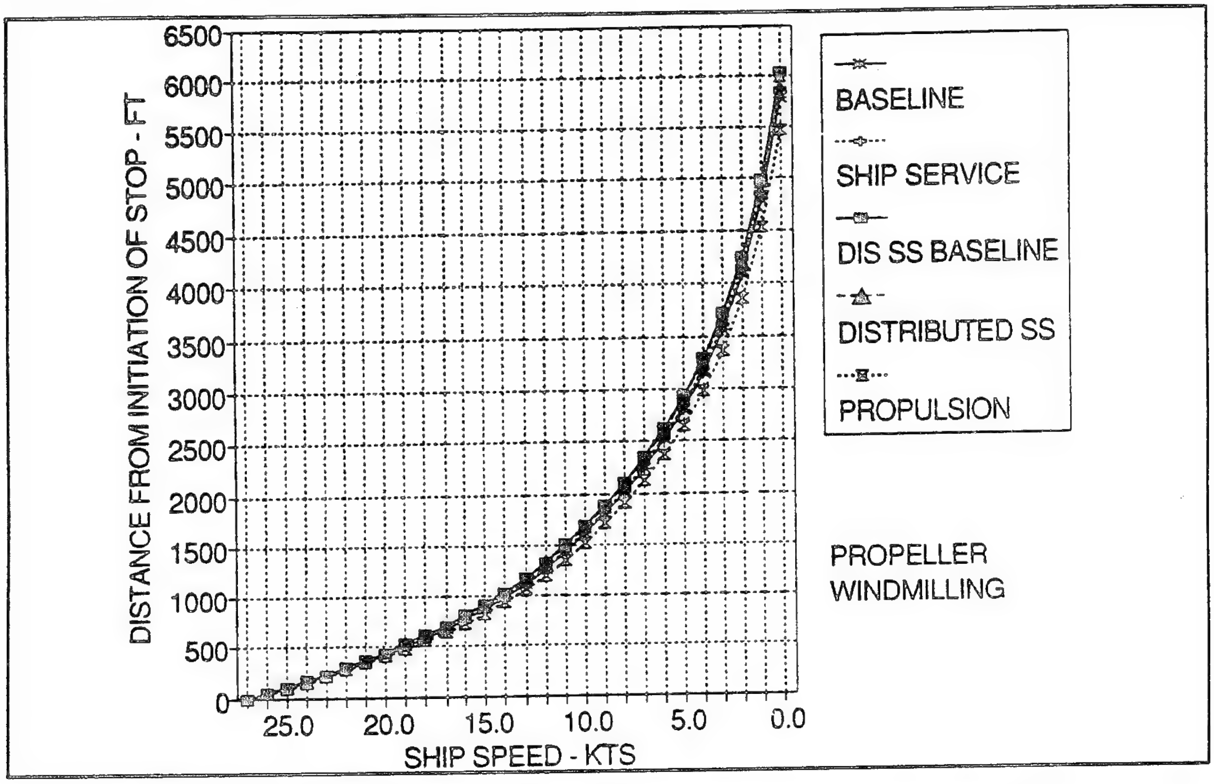

Figure 4-4. Coasting Distance of the Corvette Baseline and PEM Variants

No significant change in coasting distance was seen in the PEM variants of the Destroyer and DDG-51.

Navigational Draft

The draft of a ship can limit its access to waterways, moorings, or other operational areas of shallow depth. While draft is very much dependent on other design issues, this parameter was analyzed here since the L/B ratio and block coefficients of the ships designed were for the most part constant.

In Table 4-2 the draft of both the Corvette and Destroyer baselines along with the PEM variants are shown. The only noteworthy change is seen in the PEM propulsion variant of the Corvette in which an ~10-inch (0.8 ft) decrease in draft occurred.

4.2.1.4 Resistance

The total drag of the hullforms of the baseline and variants were compared across the operating speed range. This was performed in order to see the magnitude of change possible and to better understand the drivers of performance parameters in the study.

Table 4-2

Draft of the Corvette and Destroyer Baselines

		Draft (ft)	Change From Baseline (ft)
Corvette	Baseline	12.4	0.0
	Propulsion Variant	11.6	-0.8
	Ship Service Variant	12.2	-0.2
	Distributed SS Baseline	12.5	0.0
	Distributed SS Variant	12.4	-0.1
Destroyer	Baseline	16.0	0.0
	Propulsion Variant	16.3	+0.3
	Ship Service Variant	15.8	-0.2
	Standby SS Variant	15.7	-0.3
	Distributed SS Baseline	16.3	0.0
	Distributed SS Variant	15.6	-0.7
DDG 51	Baseline	20.7	0.0
	Ship Service Variant	20.7	0.0

In Figure 4-5 the total drag of the Corvette baseline and variants are shown. It can be seen that the propulsion variant has the only significant reduction in drag and that this difference is, for the most part, proportionally constant across the speed range when compared to the baseline. This difference is attributed to the smaller size and weight of this variant.

In Figure 4-6, the total drag of the Destroyer baselines and variants are shown. It can be seen that little difference exists between the baselines and the variants.

The total drag of the DDG-51 baseline and variant, shown in Figure 4-7, are essentially the same. This is due to the backfit approach used.

Thus, one conclusion that can be made is that the improved range characteristics of the variants at low speeds (discussed in Section 4.2.1) are due, in large part, to the shape of the SFC curve of the power plants and not the hull drag.

4.2.1.5 Manning

Mobility is typically enhanced as manning requirements decrease. This is due to decreased logistics demands. Not much data is available on manning requirements for fuel cell plants. In the ship impact study, manning requirements were assumed to be the same for the fuel cell and conventional power plants. The chemical processing involved in the fuel cell plants would require automation, thus this assumption was made.

It is known that the 200-kW PAFC plant produced by IFC is fully automated. Westinghouse's 40-kW SOFC plant is also highly automated. Both of these plants run on natural gas.

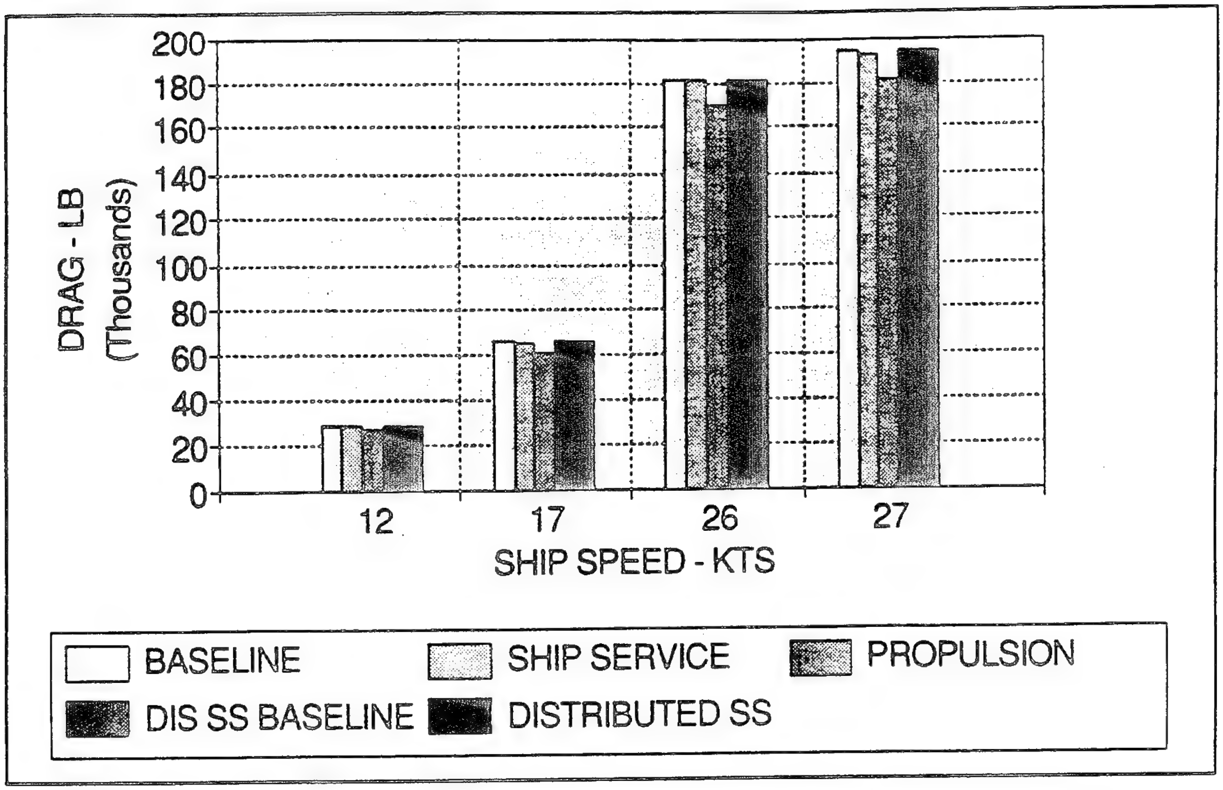

Figure 4-5. Drag Versus Speed - Baselines and PEM Fuel Cell Variants - Corvette

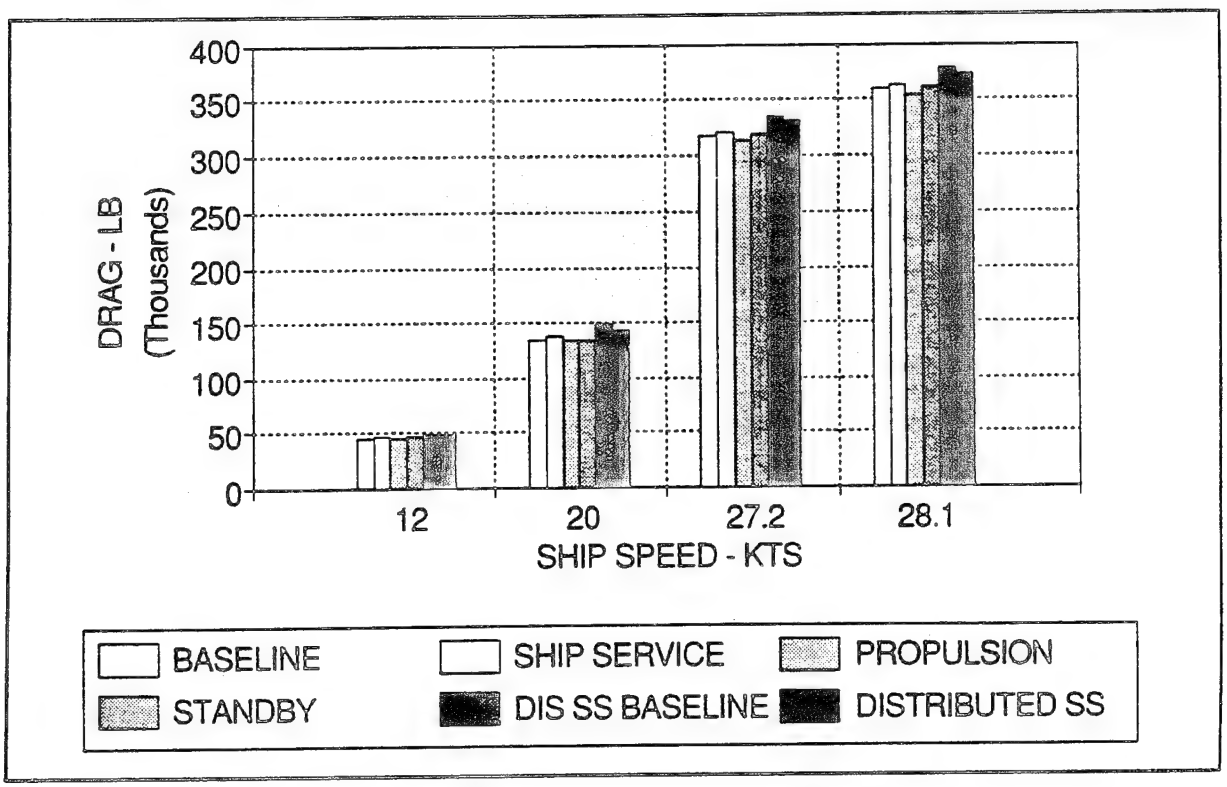

Figure 4-6. Drag Versus Speed - Baselines and PEM Fuel Cell Variants - Destroyer

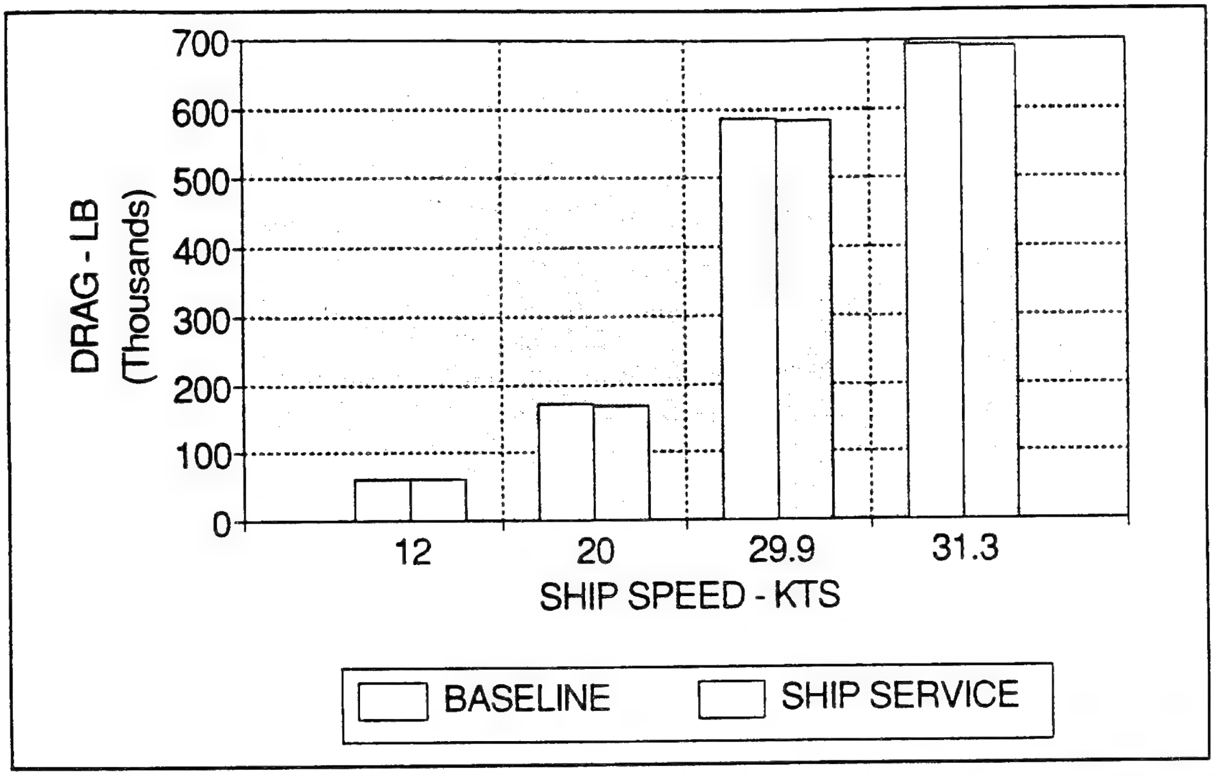

Figure 4-7. Drag Versus Speed - Baselines and PEM Fuel Cell Variants - DDG-51

4.2.1.6 Maintainability

The mobility of a vessel can be greatly affected by maintenance complexity. The dependability and repairability of a system are key to the success rate of a mission.

In Table 4-3, a comparison of the service-life hours of some of the power plants used in the study are shown. The Time Between Overhauls (TBO) is shown for the conventional plants. This is the recommended time for which components of the power plants need to be replaced or rebuilt. The proven life hours are shown for the fuel cells and represent data from test cells or stacks that have been running for months or years on end (some of which are still running). The hours are based on manufacturers data and are highly dependent on duty cycle. Where known, values of performance degradation are shown. Thus, the numbers for both types of power plants shown provide a crude means of comparison of system longevity.

The PAX diesel in Table 4-3 has numbers for minor and major overhauls. The minor overhaul time is for the replacement of the topside (head) of the diesel. The major overhaul time is to rebuild the whole engine. A typical major overhaul of a diesel engine costs up to one-third the initial cost of that engine.

The CAT 3412 diesel generator has an overhaul time of 10,000 hours in which the whole engine is rebuilt. It should be mentioned that Caterpillar has a design development goal of 20,000 hours for minor and 40,000 hours for major overhauls.

The overhaul time for the LM2500 is for "shore-based major repair" in which some components of the gas turbine require maintenance that cannot be performed onboard the ship.

An overhaul time of five to ten years was specified by IFC for their 200-kW PAFC plant. This plant runs on natural gas.

Table 4-3

Service-Life Hours of Conventional and Fuel Cell Power Plants

Plant Type	Time Between Overhaul	
	Minor	Major
PAX Diesel Propulsion CAT 3412 Generator GE LM2500	9000 -- 	18,000 10,000 7,000
	Proven Performance	
	Proven Life Hrs	Degradation Mv/Per Khrs
PEMFC, 4 Cell, 0.38 ft^2 Stack MCFC, 4 ft^2 Stack PAFC* SOFC, Core Supported Tube SOFC, Plant, Unsupported Tubes	57,000 10,000 >15,000 40,000 5,000	1 5 3 7
*Some production plants boast a 43,000 to 83,000 hour TBO.		

Table 4-4 shows the hours of operation required from the power plants on the Corvette and Destroyer based on their mission profiles and a 30 year life.

Table 4-4

Required Hours of Operation for the Corvette and Destroyer Power Plants

	Plant	Approximate Life Hours Required
Corvette	GT Propulsion Diesel Propulsion SS Diesels Standby SS Diesel	13,000 69,000 82,000 4,000
Destroyer	ICR GT Propulsion & SS Standby SS GT	81,000 45,000

On comparing Table 4-3 and Table 4-4, it can be seen that the potential exists for operation of the fuel cells without overhauls or major repair items occurring during a good portion of the life of the ship. This is based on the premise that the additional diesel reforming and sulfur removal equipment, required for the marinized version of the FC plants, have equal longevity as demonstrated by the stack. Testing is required to demonstrate the longevity of this equipment.

Based on the percent performance losses known, the PEM cell would degrade 10.6% in output over an 80,000 hour life and the SO fuel cell would degrade 75% over 80,000 hrs, assuming no maintenance.

From an ease of maintenance standpoint, it is expected that routine short-term maintenance procedures will not be labor intensive for the fuel cell plants examined. Tasks would involve inspections of fittings, pipes, pressure vessels, etc. and replacement of filters.

For larger maintenance items, such as overhauls or major repairs, the potential exists, by design, for the fuel cell plants to require less down time and manpower. This could be accomplished by using a modular design philosophy which takes advantage of the design flexibility of fuel cell plants.

Currently, conventional power plants do not offer much flexibility of arrangement due to interface requirements (i.e., shaft, intake, uptake), size availability and shape availability (high length-to-width ratio is typical).

Fuel cell plants can be designed to almost any shape or size without penalizing efficiency. However, by economy of scale, weight to power ratios improve as size increases. Nonetheless, several small plants can do the job of a large plant without a significant penalty in weight and size. Also, the redundancy offered by several small plants would increase permitted repair time thereby decreasing manpower requirements. Smaller plant sizes also allow for spares to be kept and manageable replacement to take place.

Another design philosophy that could be pursued with fuel cell plants is modularizing the stack in a large plant and keeping the balance of plant as one unit. This would allow rapid replacement of a failed portion of the stack which might otherwise have required the complete removal of the stack for repair.

4.2.2 Survivability

4.2.2.1 Signatures

The assessment of the pay-offs in survivability for an improved signature is not easy to assess. This combined with the fact that data on modern or advanced weapon system sensors is hard to obtain, due to its classified nature, makes unclassified quantitative analysis impossible. For this reason, relevant data for various types of signatures of the baselines and variants are presented but military pay-offs are not assessed. This will be left to the appropriate agencies. Instead, the variants will be compared against the baselines and apparent large changes in the parameters being examined will be considered as a significant change for the better or for the worse.

Radar/Optical

Radar and optical signatures are based on size, shape, and material characteristics (structure and coverings) of the ship. For the optimized fuel cell variants, size and shape were the only parameters that were allowed to vary.

The shape of the fuel cell variants were for the most part constant, since hull block coefficients and length-to-beam ratios were not allowed to vary much. Also, superstructure size was not allowed to grow out of proportion with the hull to the extent that stability of the ship was degraded.

Thus, the largest change that took place in the fuel cell variants, that related to radar/optical signatures, was that affecting the ship size. In order to compare the sizes of the variants against the baselines, above-waterline cross-sectional areas were calculated for each ship in the longitudinal and transverse directions.

Ship cross-sectional areas are shown in Figure 4-8 for the PEM variants of the Corvette. Similar areas are shown in Figure 4-9 for the PEM variants of the Destroyer and its baselines. The PEM propulsion variant of the Corvette has the only noticeable reduction in area, mostly due to the absence of exhaust stacks.

No change in cross-sectional area existed for the DDG-51 ship service variant since the power plants were backfitted.

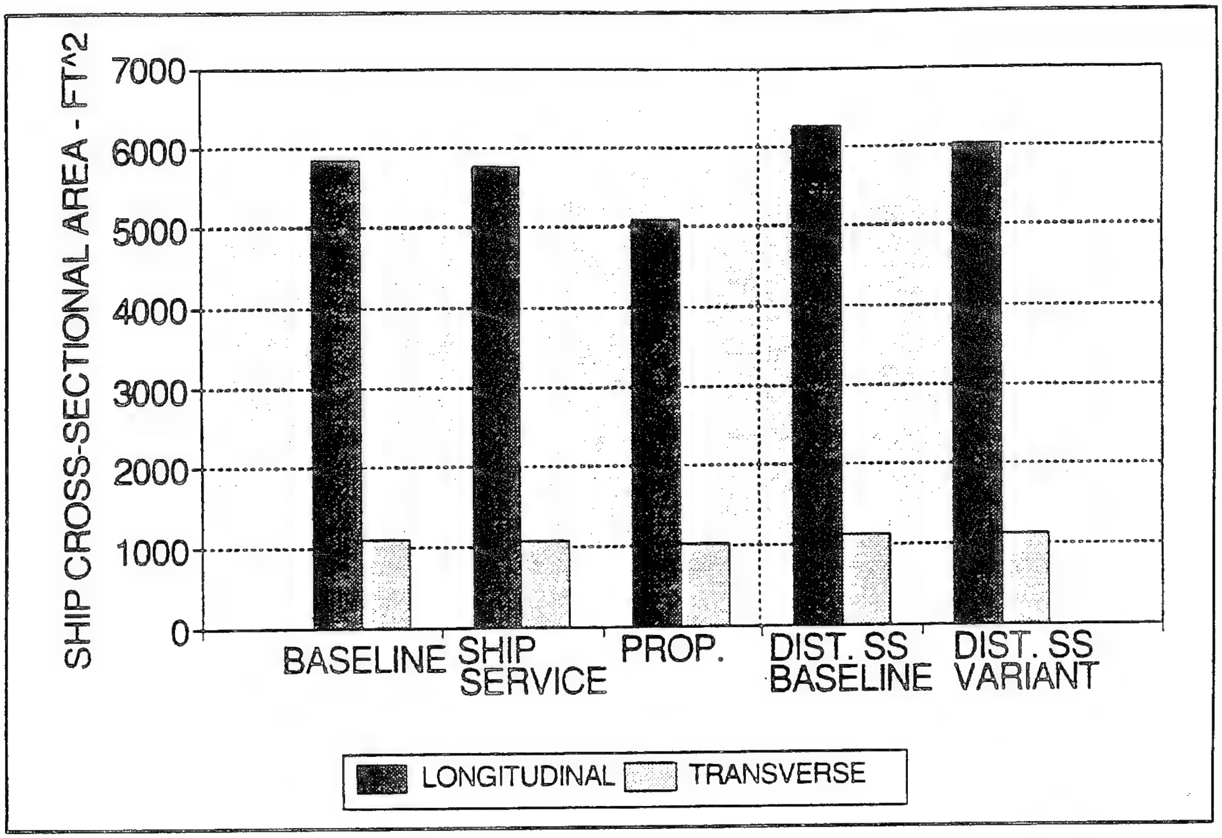

Figure 4-8. Cross-Sectional Areas - Baselines and PEM Fuel Cell Variants - Corvette

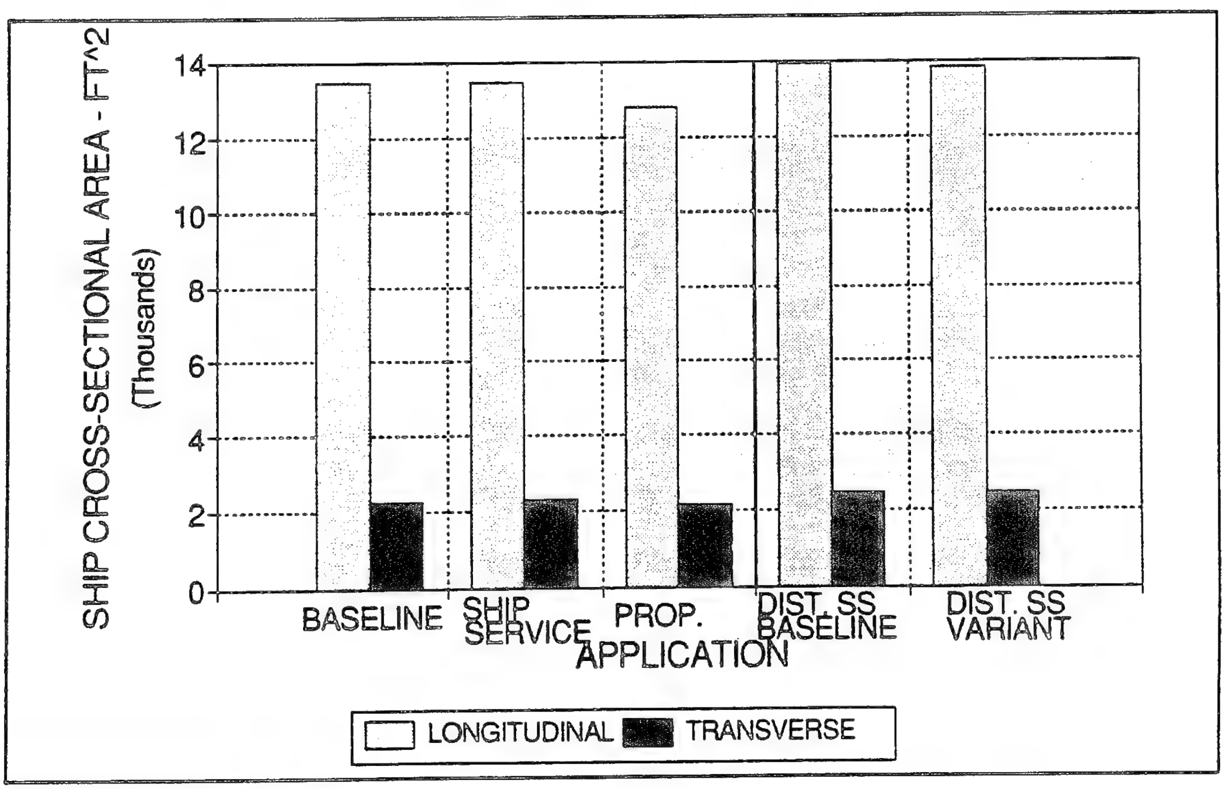

Figure 4-9. Cross-Section Areas - Baselines and PEM Fuel Cell Variants - Destroyer

Infrared

A large contributor to the IR signature of a ship is heat rejected through its exhaust stacks. In order to compare this characteristic for each ship, a backfit scenario was used in which equivalent ship service and propulsion power was used (same shaft power out).

Figure 4-10 shows the heat rejected to the atmosphere by the various power plant types installed on a Corvette operating at 17 kts. It can be seen that 3.5 to 7 times less heat is rejected by the various fuel cell types in this condition. This figure includes the effect of combining the propulsion diesel output at Maximum Continuous Power (MCP) and the SS diesel output for the baseline, while fuel cells are used for propulsion and ship service in the fuel cell variants.

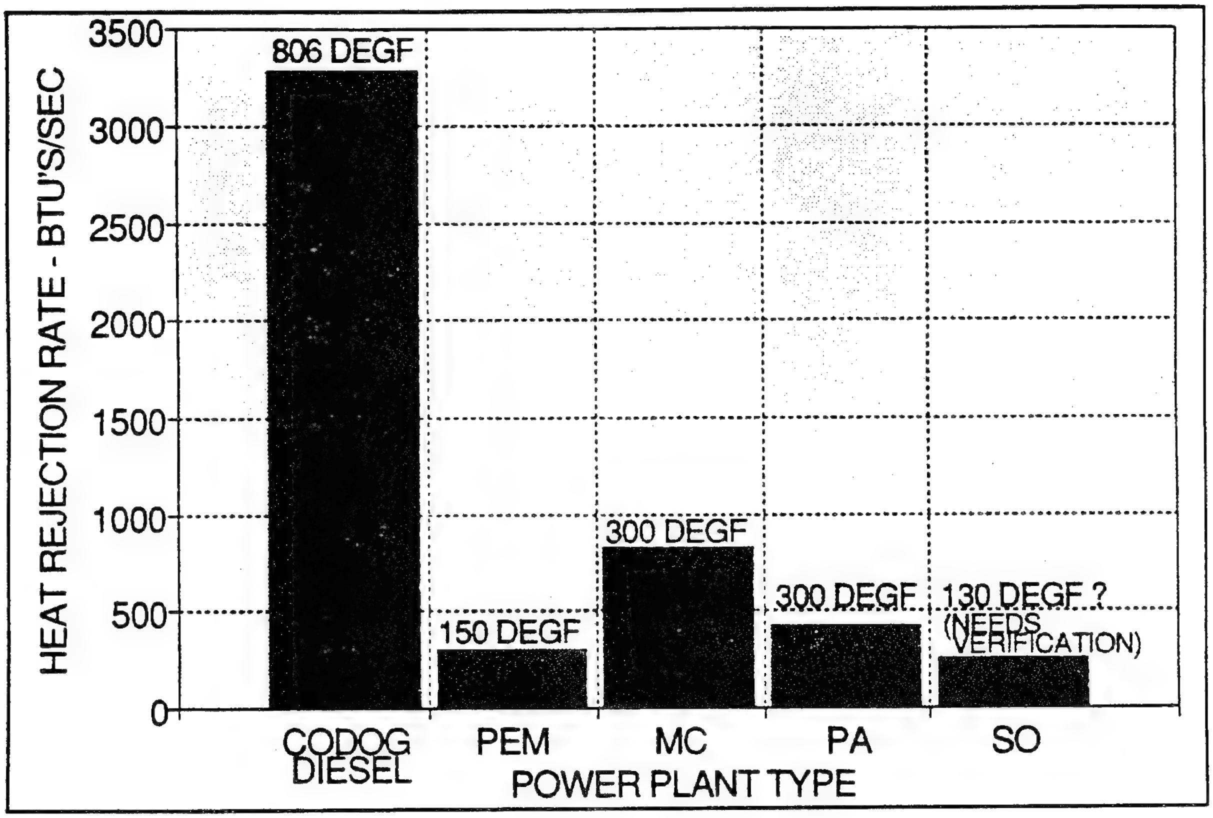

Figure 4-10. Heat Rejected to Atmosphere - Corvette Operating at 17 Knots

Figure 4-11 shows the heat rejected by the corvette operating at 27 kts. The baseline gas turbine is at MCP in this case. Here, the heat rejected through the exhaust is reduced 10 to 20 times by the use of the fuel cell plant.

In Figure 4-12, the heat rejected through the exhaust of plants of equivalent electric power are shown for the Destroyer operating at 28.1 kts. It can be seen that the amount of heat rejected by the fuel cell plants is about 10 to 20 times less than that of the ICR GT with PDSS. It can be seen, when comparing Figures 4-11 and 4-12, that the same amount of heat is rejected by the Destroyer baseline as is rejected by the Corvette baseline even though the propulsion power on the Destroyer is about twice that of the Corvette. This is due to the ICR type of gas turbine that is in the Destroyer.

It appears, therefore, that significant reduction of infrared signatures may be expected from fuel cells due to the combined effect of reduced exhaust temperature and exhaust flow.

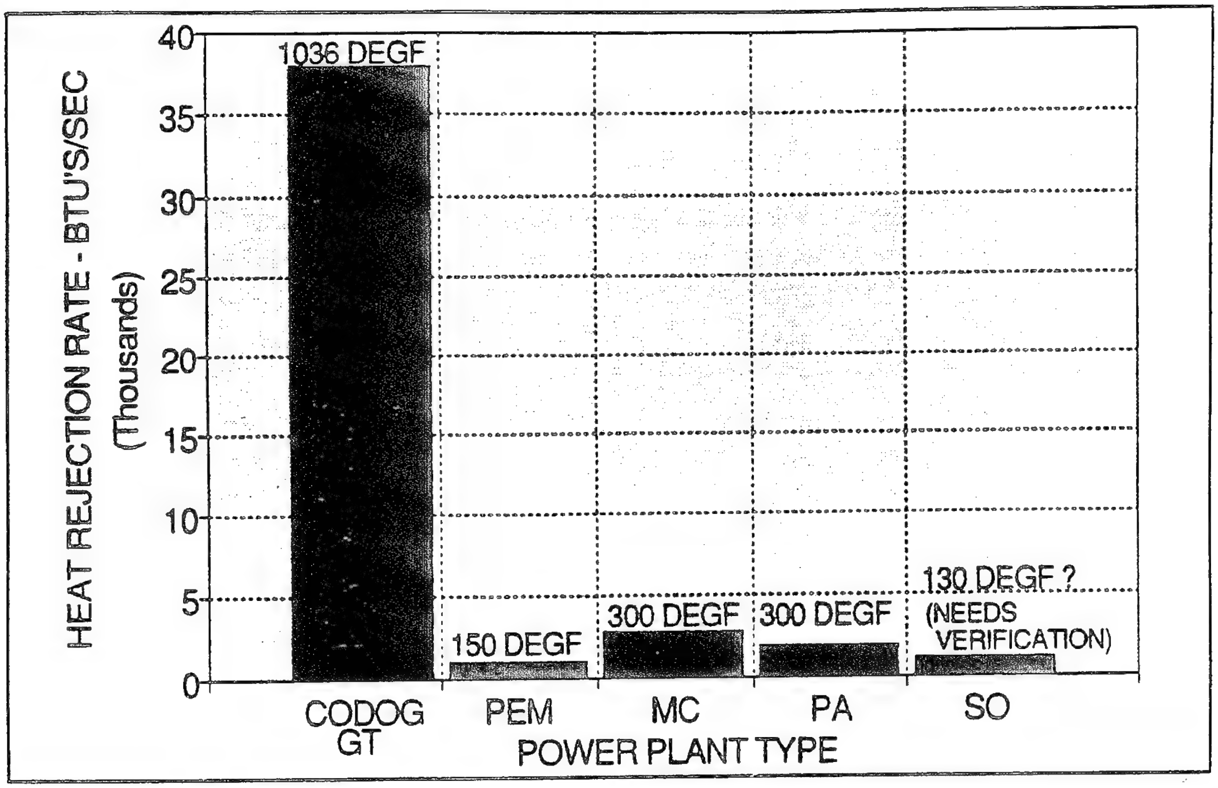

Figure 4-11. Heat Rejected to Atmosphere - Corvette Operating at 27 Knots

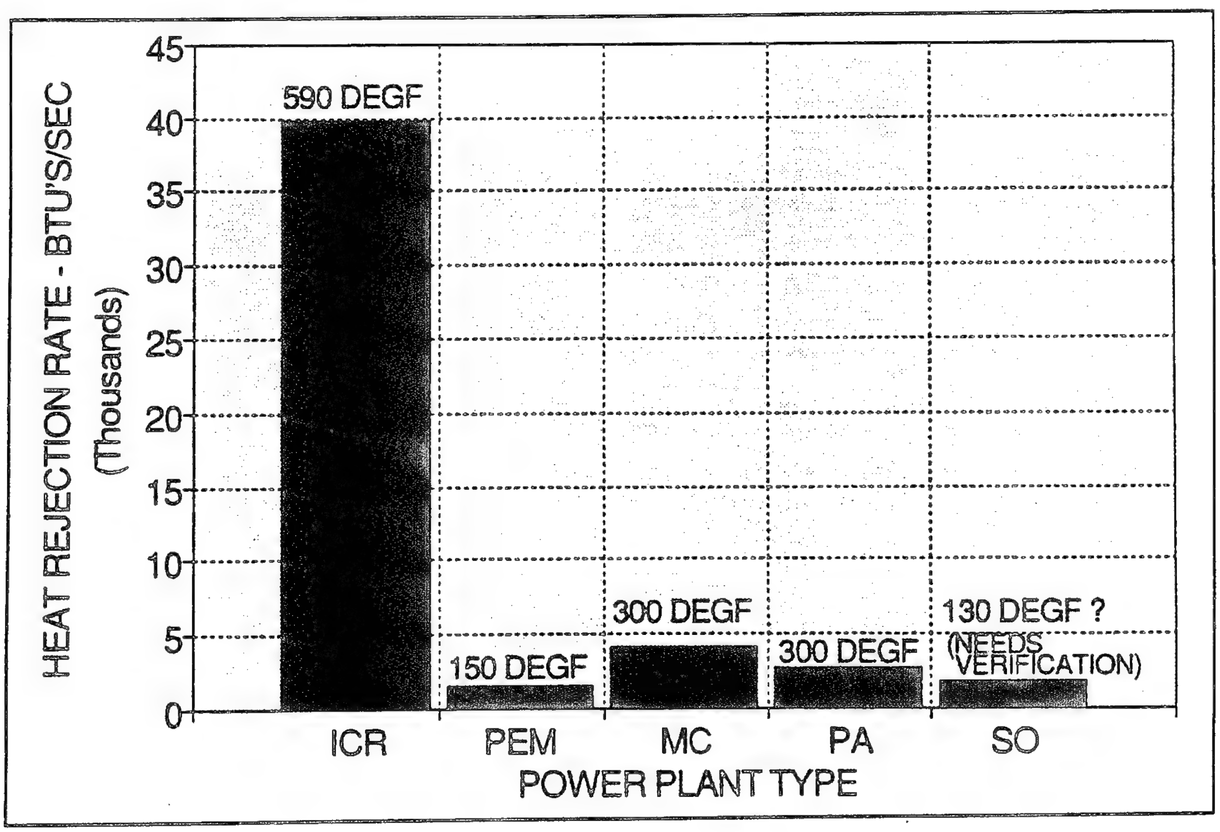

Figure 4-12. Heat Rejected to Atmosphere - Destroyer Operating at 28.1 Knots

Acoustic

An assessment of noise generated through the structure of a hull by the power plants examined would be difficult without detail design data. Qualitatively, a few things can be noted.

The primary source of noise from the fuel cell plants would be from turbo-compressors moving pressurized air and fuel through the plants. The inherent electric drive of the fuel cell plants would eliminate gearbox noise. Noise levels should be less than the noise of conventional power plants, especially diesels.

The airborne noise analysis of Section 4.2.1.2 may be used to provide an order of magnitude for acoustic signature reduction permitted by fuel cells.

Magnetic

The potential exists for the reduction of magnetic signatures by using PEMFC plants and to a lesser degree for the PAFC type due to their low operating temperatures. The low temperatures could facilitate the use of composite or plastic materials which would have low magnetic signatures.

Wake

No significant pay-offs in wake signatures were found for the variants. A ship's wake is largely influenced by its length-to-beam ratio, block coefficient and propeller configuration. These parameters were held almost constant among the variants created.

Pressure

Based on similar arguments as above, the pressure signatures of the PEM variants were deemed to be comparable with the baseline ships.

4.2.2.2 Damage Tolerance

Of the various parameters examined in the assessment, very little is known about the damage tolerance of the fuel cell plants. Thus, testing and demonstration of fuel cell plant characteristics in this area are needed. Nonetheless, what is known about the various aspects of damage tolerance, as relates to fuel cells, are discussed in this section.

Shock and Vibration

No known testing has been performed on the fuel cell types examined in this study in the area of shock and vibration. However, fuel cells have been used in spacecraft for decades, thus the design of fuel cells for high levels of acceleration and vibration is possible.

Fire

The susceptibility of fuel cell plants to fire is an area that requires further assessment. It is noted that the PEMFC and PAFC stacks operate at temperatures that are lower than conventional power plants. On the other hand, the presence, in the reformer and stacks, of highly volatile fuels (pure hydrogen) may present specific fire related concerns.

Flooding

As with conventional plants, intake and exhaust ducts can be routed in such a way as to prevent damage to the internal components of fuel cell plants that otherwise would have resulted from flooding. How well the system could recover otherwise is left to testing.

Modularity/Redundancy/Repairability

Fuel cell plants lend themselves well to flexibility of design. This in turn allows for the utilization of modular concepts. As is discussed in Section 4.2.6, plant efficiency does not vary with the size of the plant and any size plant can be built (within reason). One drawback is that the weight-to-power ratio increases as plant size decreases. This is reflected in the greater displacement of the distributed ship service variants which have about the same power requirements as the direct replacement ship service variants. Nonetheless, the weight penalty is small to moderate and is less than would be incurred by conventional SS plants.

From a survivability standpoint, modularity can:

- Allow a large portion of a plant to remain operational after a hit (modular stack)
- Provide for a reduction in repair time because of:
  - Smaller, more manageable components
  - A greater onboard inventory of components due to size
  - A greater availability in the Navy supply due to commonality of parts
- Allow a large portion of the plants to remain operational after damage (modular plants).

Environment Sensitivity

Testing and analysis of the vulnerability to the environment of FC plants needs to be performed. This would include, for instance, the effects of nerve agents, heavy smoke, pollutants, salt, etc. in the air supply.

4.2.3 Environmental

4.2.3.1 Fuel Saved

The energy savings that are afforded by the fuel cell variants were examined by determining the amount of fuel consumed in the lifetime of each ship. Mission profiles outlined in Chapter 3.0 were used and a 30-year life was assumed.

It was found that fuel savings were present in all of the PEM ship variants when compared to their respective baselines. These amounts can be seen in Figures 4-13 through 4-15. These figures show that as ship size, and thus power level, increases the energy savings increase. The most significant savings are manifested in the DDG-51 ship service backfit, Figure 4-15. In this case, the fuel cells replace three gas turbine ship generators which not only have poor efficiency at small load fractions, but incur efficiency losses in the conversion of mechanical energy into electrical energy.

4.2.3.2 Pollutants

The pollutant levels in the exhaust of the baselines and variants were studied. The five major types of pollutants considered were:

- Carbon Monoxide
- Nitrous Oxides
- Hydrocarbons
- Sulfur Dioxide
- Carbon Dioxide.

Fuel cells typically have extremely low levels of pollutants in their exhaust. Fuel cells are intolerant of sulfur, thus they require the elimination of this element during fuel processing prior to the fuel cell reaction. The approach that was taken to eliminate the sulfur in this study was to assume that the sulfur would be

burnt after it was extracted from the fuel. Since the proportion of sulfur in diesel fuel was assumed to be constant, any reduction in SO_2 shown in this section is from reduced fuel consumption onboard the variants. It should also be noted that the equipment onboard the fuel cell variants that remove the sulfur and burn it can be replaced with filtering beds of equal size and weight that store the sulfur. These beds could be replaced periodically to provide complete elimination of sulfur emission into the atmosphere.

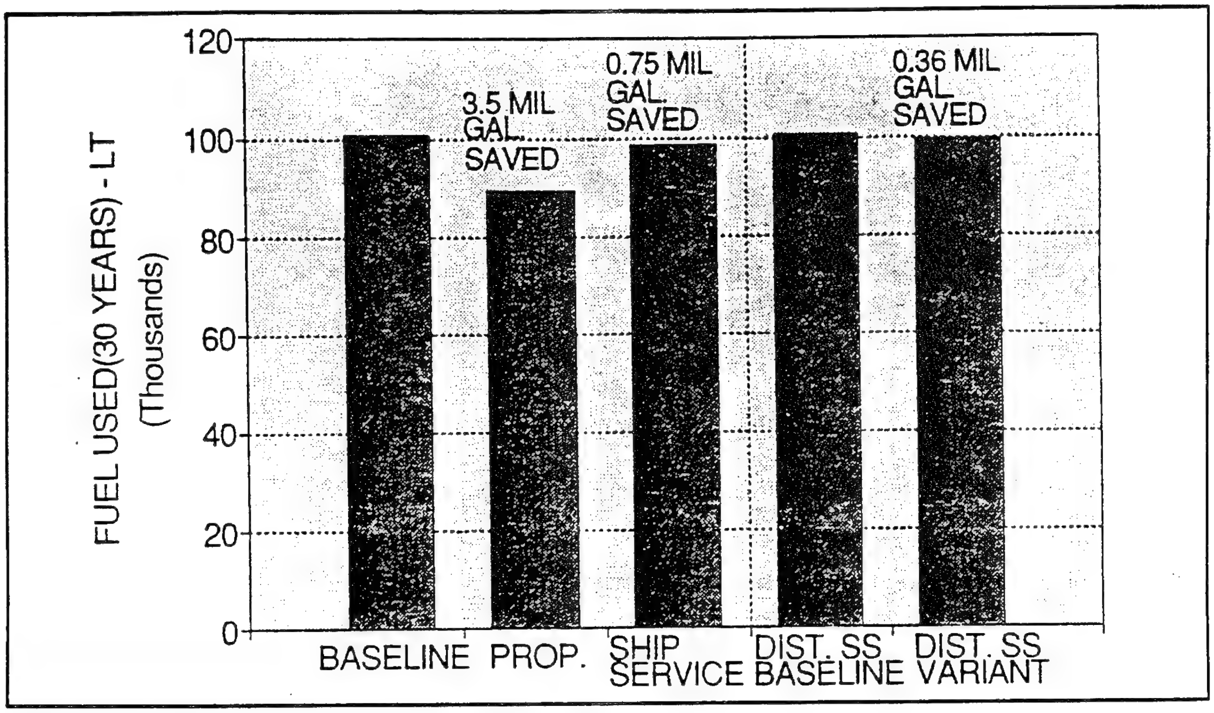

Figure 4-13. Fuel Consumed Over Life of Ship - Baselines and PEMFC Variants of Corvette

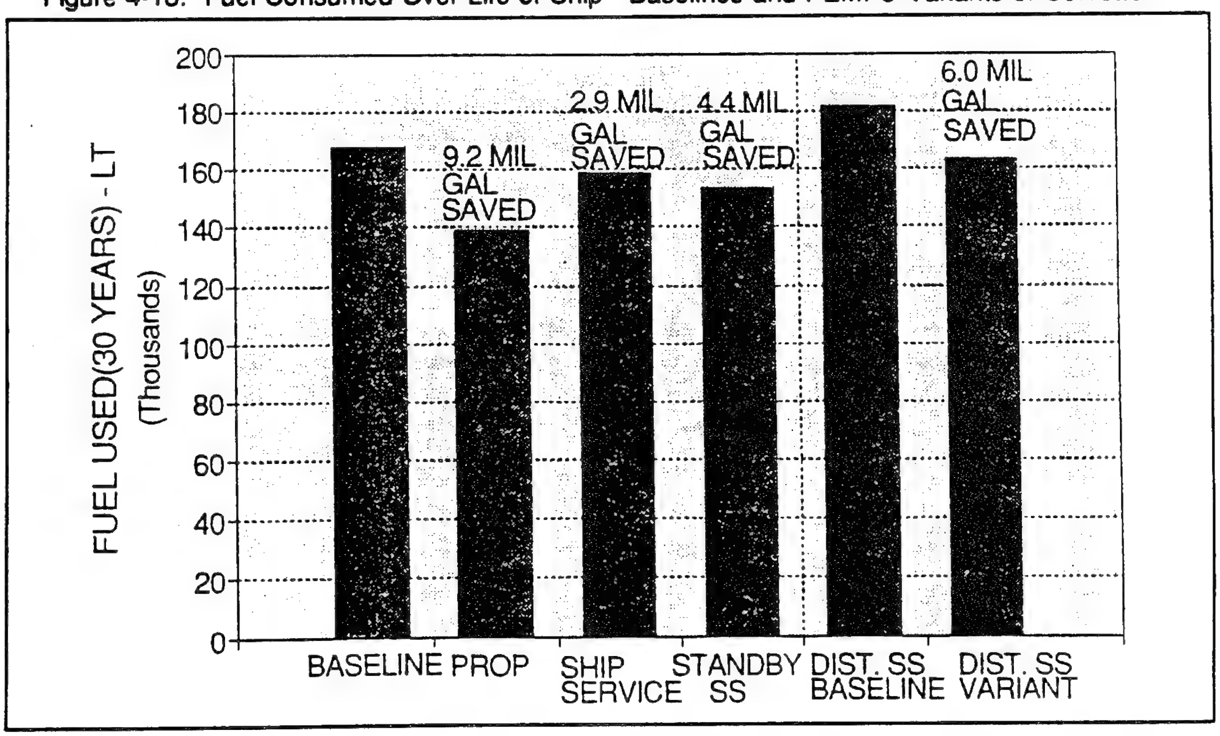

Figure 4-14. Fuel Consumed Over Life of Ship - Baselines and PEMFC Variants of Destroyer

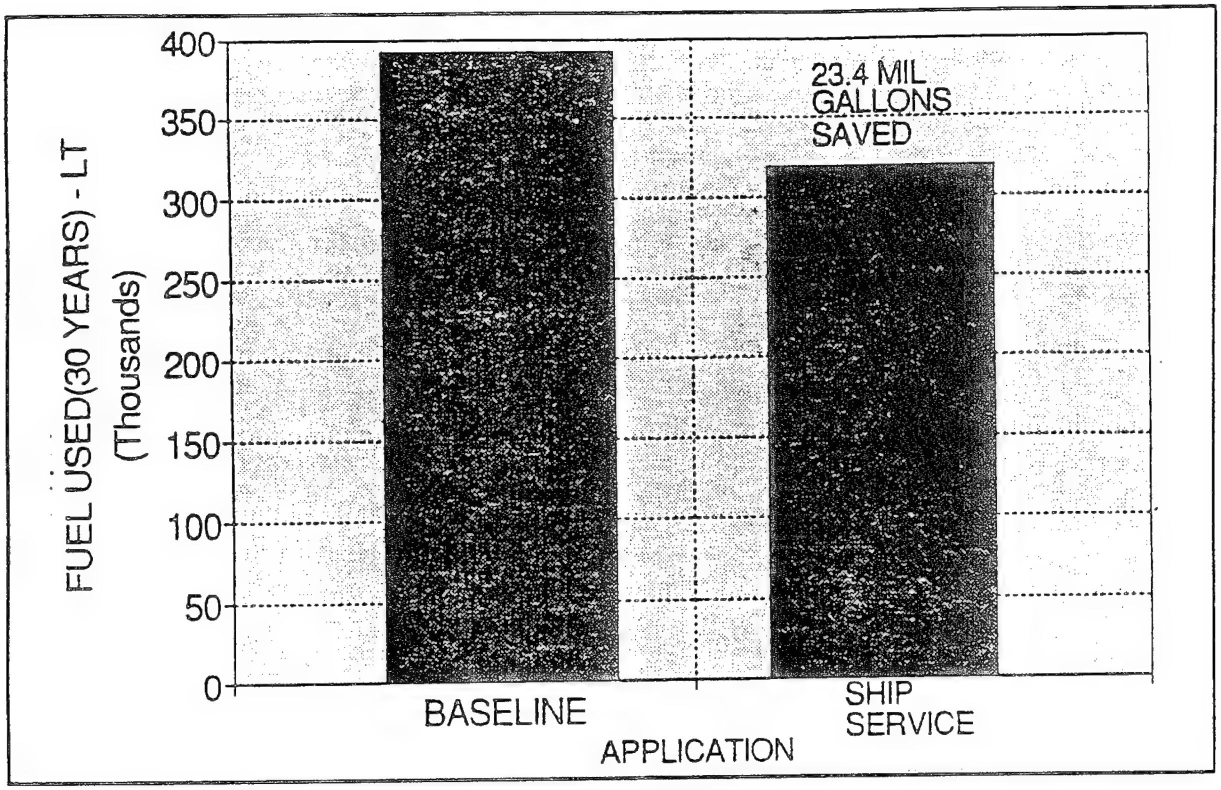

Figure 4-15. Fuel Consumed Over Life of Ship - Baselines and PEMFC Variant of DDG-51

Figure 4-16 shows the pollutants emitted to the atmosphere in the lifetime of the Corvette baseline and PEM propulsion variant. It can be seen that significant improvements in the pollutant levels are gained by use of a PEM fuel cell plant. Similar improvements are possible using the other fuel cell types examined in this report.

Figure 4-17 shows pollutant levels that are more dependent on fuel consumption rather than chemical reactions taking place in the plants shown. SO_2 promotes acid rain and CO_2 promotes "greenhouse" effect, thus both chemicals are likely to become targets for further regulations.

4.2.4 Weapons

4.2.4.1 Power Conditioning

Future U.S. Navy weapon systems will more than likely operate on DC power. This is evident based on the development of pulse weapons and DC buses that the Navy is sponsoring. Since fuel cells produce DC out, the need for power conditioning will be reduced. This will save weight and avoid the losses associated with power conditioning equipment.

4.2.4.2 Overload Tolerance

While the fuel cell has great overload capability, typically fuel processors and air handling subsystems do not. However, the designer can build in a small amount of reactant storage to handle anticipated overloads.

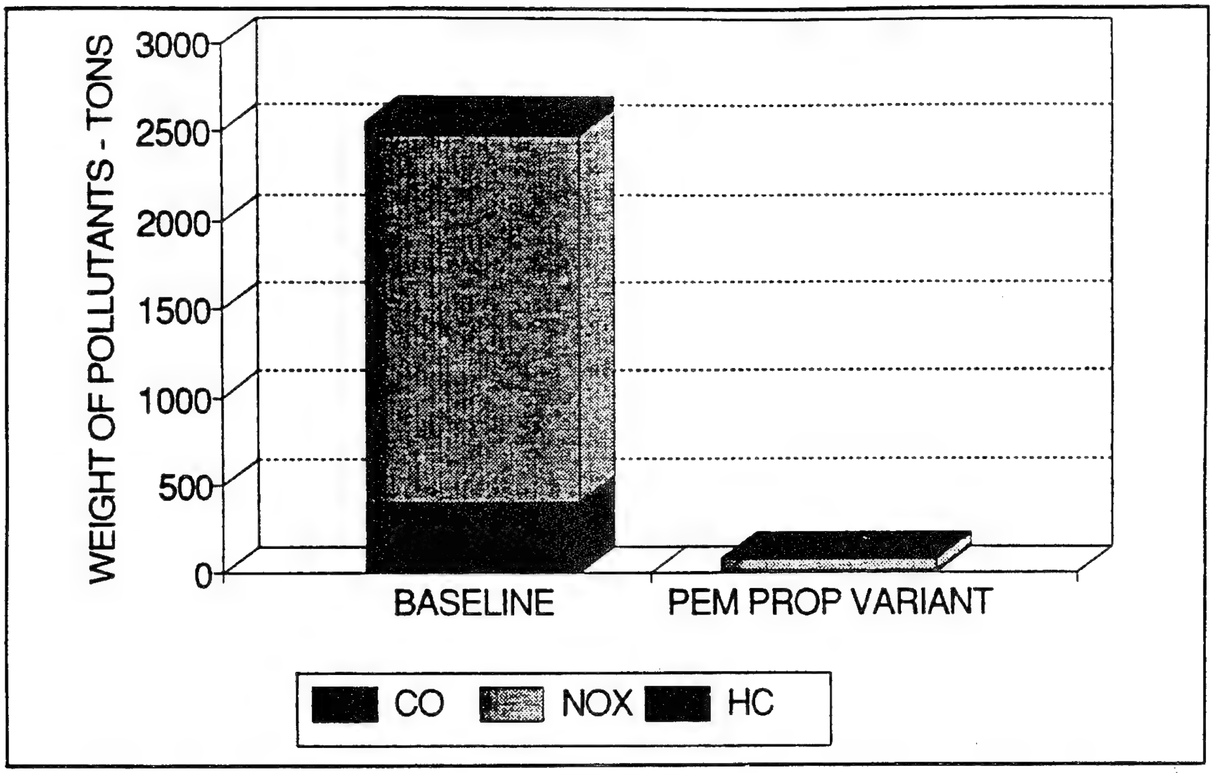

Figure 4-16. Pollutants Emitted to Atmosphere During Life of Corvette (CO, NOX, HC)

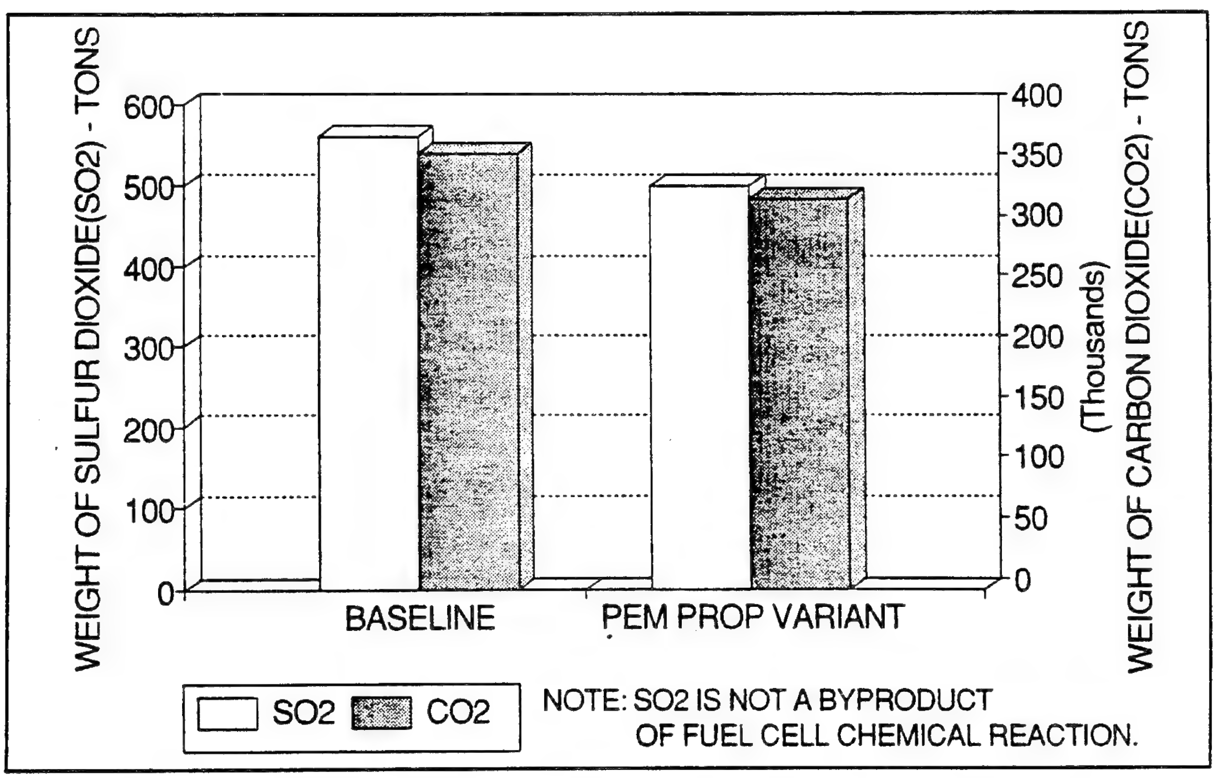

Figure 4-17. Pollutants Emitted to Atmosphere During Life of Corvette (SO2, CO2)

4.2.4.3 Propulsion Derived Power

Studies suggest that the best suited power system for pulse weapons on a ship would be one in which power is taken from propulsion plants. Dedicated power plants for pulse weapons (having large peak power requirements) are required to be massive for any kind of lengthy engagement in battle. Thus, the requirement for an integrated electric propulsion system is envisioned for future naval combatant designs, since these systems make available the power levels needed at little expense to the ship design. Fuel cell systems appear to be an attractive candidate for an integrated propulsion/weapon power system based on the benefits that have been demonstrated in the propulsion variants throughout this chapter.

4.3 Cost

4.3.1 Introduction

As part of the cost support for the Enabling Technologies Project within the 6.2 Surface Ship Technology Block Program, a cost assessment was conducted to determine the cost impacts of replacing propulsion and ship service power systems aboard Baseline ships with fuel cell systems. The cost impact of fuel cell systems are investigated for two different types of conceptual Baseline ships, a Destroyer and a Corvette. By incorporating each fuel-cell powered system instead of the original Baseline system, each Baseline ship is transformed into a fuel-cell powered Variant ship.

This cost assessment emphasizes the cost *difference* between each ship Variant and its respective Baseline, i.e., cost deltas. Cost deltas for Life Cycle Cost (LCC), Operating and Support (O&S) Cost, Acquisition and Basic Construction Cost (BCC) were estimated for the Baselines and their Variants. No ship costs were estimated for Research, Development, Test and Evaluation (RDT&E), or for Disposal or combat system cost. These different categories of cost are defined in Appendix F.

Ship designs and cost estimates were made for shipboard arrangements of Proton Exchange Membrane (PEM) fuel cell systems. A total of seven PEM system arrangements were considered. For the Destroyer concept, there are four Variant systems: (1) Stand-by Ship Service Power (SbSSP), (2) Direct Replacement of Ship Service Power (DRSSP), (3) Distributed Ship Service Power and (DiSSP) (4) Direct Replacement of Propulsion Power (DRPP). The Corvette concept has the same Variant systems except for standby ship service power.

Five types of power systems were proposed for this study:

(1) Baseline Systems which include Gas Turbines, Diesel Generators and machinery within the conceptual Integrated Power System (IPS)
(2) Proton Exchange Membrane Fuel Cell (PEMFC)
(3) Molten Carbonate Fuel Cell (MCFC)
(4) Phosphoric Acid Fuel Cell (PAFC)
(5) Solid Oxide Fuel Cell (SOFC)

All five systems were analyzed based on qualitative technical risk and projected cost impacts compared to the respective Baseline ship. Originally, ship cost impacts from the latter three types of fuel cell systems were to be evaluated. Due to project redirection, no cost estimates were made for these ships using these other types of fuel cell systems. However, analysis of these other fuel cell system costs and technical risk, relative to those of the PEM system, allows preliminary analyses and conclusions to be made as to whether these "alternatives" may provide a cost benefit.

Acronyms and abbreviations are used for cost categories, fuel cell system arrangements and fuel cell system types throughout the remainder of this report, and are listed in Table 4-5 for easy reference.

Table 4-5

List of Acronyms and Abbreviations Related to Cost

I.	Cost Categories:	
	RDT&E	Research, Development, Test and Evaluation
	BCC	Basic Construction Cost
	SWBS	Ship Work Breakdown Structure
	CER	Cost Estimating Relationship
	MCC	Major Category Codes
	GFM	Government Furnished Material
	O&S	Operating and Support Cost
	LCC	Life Cycle Cost
	NPV	Net Present Value
II.	Fuel Cell Systems - Subsystems:	
	BOP	Balance of Plant - Chemically Processes and Circulates Fuel
III.	Fuel Cell Systems - Shipboard Arrangements:	
	SbSSP	Stand-by Ship Service Power
	DRSSP	Direct Replacement of Ship Service Power
	DiSSP	Distributed Ship Service Power
	DRPP	Direct Replacement of Propulsion Power
IV.	Fuel Cell Systems - Types:	
	PEM	Proton Exchange Membrane Fuel Cell System
	MC6	Molten Carbonate Fuel Cell System (Run at 6 Atmospheres)
	PA	Phosphoric Acid Fuel Cell System
	SO	Solid Oxide Fuel Cell System

The cost numbers shown herein are rough order of magnitude (ROM) estimates. The estimating techniques used were similar to those used to produce a budget level estimate; however, the conceptual nature of the design does not permit a higher classification to be assigned.

There will inevitably be some error associated with any cost estimate performed on a technology primarily because of its exploratory development nature. This error is due, in part, to the uncertainty associated with the design or the technology that is reflected in the specification estimates. Unless otherwise stated, all cost figures shown in this report are in 1993 constant dollars.

Ship acquisitions are typically for one lead ship and multiple follow ships. The lead ship cost is higher than follow ships because it includes to non-recurring costs, and progress on the labor learning curve has not yet begun. In this assessment, the first follow ship LCC deltas were compared for the various PEM fuel cell ship applications.

4.3.2 Approach

Subsequent to the initial cost study of the fuel cells, amendments are anticipated as assessment experience is gained and as supporting assessment capabilities are realized.

The assessment of each ship's cost was conducted with the aid of: (1) cost estimating relationships (CERs) provided by NAVSEA 017, Cost Estimating and Analysis Division, for the DDG-51 "Arleigh Burke" class of guided-missile destroyers and (2) Manufacturing Complexities, MCPLXS, derived from General Electric's parametric cost model, PRICE-H (Parametric Review of Information for Costing and Evaluation - Hardware).

Cost estimating relationships or CERs represent shipyard labor and overhead rates, material cost per unit weight, ship engineering and assembly rates, facilities cost of money and profit. NAVSEA 017 provided CERs at the system/sub-system levels for the ship propulsion and electrical systems and at an aggregate level for the remaining ship systems. The PRICE model is a group or system of cost estimating and evaluation models and auxiliary programs. PRICE H is a computerized cost estimating model that estimates cost using a parametric approach. The PRICE H model converts a combination of input variables to cost using Manufacturing Complexity factors. These input variables may include parameters such as weight, quantity, schedule, design inventory and the fabrication process.

The basic approach used to estimate the costs of the Destroyer and Corvette Baselines and their respective PEM fuel-cell powered Variants is outlined in Figure 4-18. Methods and models used to develop NPV, LCC, O&S, Acquisition, BCC and system costs are defined in further detail in Appendix F. Details on Manufacturing Complexities can be found in Appendix I, while Appendix J describes the approach to a greater level of detail.

The DDG-51 class CERs, provided by NAVSEA 017, needed to be increased for the Destroyer and Corvette concepts. Having overall dimensions and displacements significantly less than the DDG-51 class, each Baseline ship concept has CERs greater than those for the DDG-51 class. There is a common trend known as "economies of scale" in which, for the Baselines in this study, a decrease in ship size correlates to a non-linear increase of CERs, e.g., man-hours will increase per long ton. For example, a shipbuilder typically wants to maintain a minimum level of infrastructure such as manpower, storage areas, offices, etc. These costs may remain relatively fixed over a wide range of ship sizes (3000 to 8000 long tons). Adjusted CERs, which compensate for "economies of scale", are non-existent for the Destroyer and Corvette Baselines because they are in the conceptual design stage. Therefore, MCPLXS factors were used to account for the shipbuilder's fixed costs which, in a sense, represent "adjusted CERs" for the Baseline concepts.

4.3.3 Results

4.3.3.1 Life Cycle Cost Impacts

Thirty year LCC impacts, based on currently recommended O&S scenarios for Baseline and PEM fuel cell systems, are estimated for all Destroyer and Corvette concepts. The LCC estimates for all Destroyer Variants were higher than that of the Destroyer Baseline. None of the Destroyer Variants are found more economical than the Baseline. Only the standby ship service power (SbSSP) Variant, having a LCC of less than 1% above the Baseline ship, has a negligible positive cost delta relative to the Destroyer Baseline.

Regarding the Corvette Variants, the LCC of the direct replacement ship service power (DRSSP) Variant is nearly the same as the Baseline LCC, or about 0.3% less than the Baseline. The Corvette Baseline, however, would obviously require RDT&E investments. The other two Corvette Variants had minimal LCC deltas as well, less than 1.6% higher than the Corvette Baseline.

Note that all Distributed Ship Service (DiSSP) variants are compared to the baselines with centralized ship service power systems. Therefore, it is anticipated that a small cost decrease would be seen when comparing these DiSSP variants to baselines having distributed ship service power systems.

Table 4-6 summarizes the LCC impacts for all first follow ship Variants.

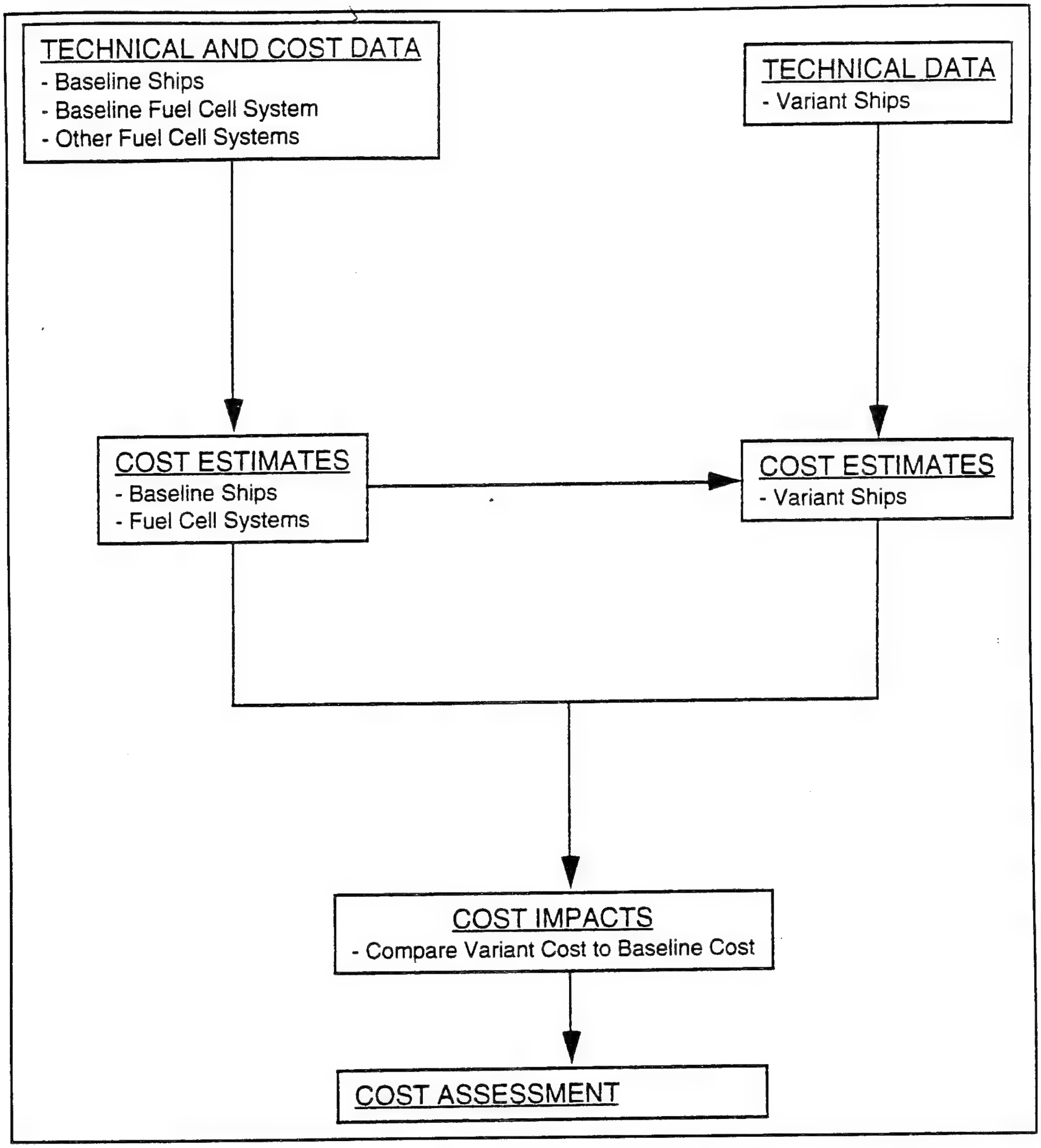

Figure 4-18. Comparative Technology Assessment Approach for Fuel-Cell Powered Variants Versus Their Respective Baselines, Destroyer and Corvette

4.3.3.2 Acquisition Cost Impacts

Unlike BCC estimates, Acquisition Cost does not serve as a useful tool in assessing specific technology impacts. Unlike LCC, Acquisition Cost is not a means for calculating available RDT&E investment. There are three main purposes for providing Acquisition Cost estimates:

(1) Demonstrate that Acquisition Cost is an approximation of actual SCN funds budgeted by the U.S. Navy. As noted earlier, Combat Systems/GFE costs were not yet estimated in this

study. Combat Systems/GFE costs are expected to be a large percentage of the Acquisition Cost. Therefore, at this stage of the study, the Acquisition Cost is an approximation of actual Navy SCN funds minus Combat Systems/GFE costs.

(2) Use each Acquisition Cost estimate as an intermediate step towards estimating LCC. LCC, for this particular study, is estimated from the summation of Acquisition Cost and O&S Cost.

(3) Define all major Acquisition Cost categories. Excluding Combat System Costs, there are two main cost drivers in the Acquisition Cost of a Lead ship of a class: BCC and "Construction Plans". For Lead Ship, BCCs presently comprise 39 to 44% of the Acquisition Cost whereas "Construction Plans" range from 45 to 50% of Acquisition Cost. Both these percentages will decline once Combat System/GFE costs are included in Acquisition Cost estimates. The "Construction Plans" cost for each ship concept was estimated with an algorithm having the following cost drivers:

a. Engineering Complexity
b. Overall Manufacturing Complexity of the Ship
c. Overall Lightship Weight of the Ship
d. Relative Design Status, e.g., R&D, Preliminary, or Production
e. Degree of Design Repeat, e.g., minimal to extensive
f. Year of Technologies on Ship

Appendix F provides a more detailed definition of Acquisition Cost and Table F.6 is the Acquisition Cost "breakdown" used for this study.

Table 4-6

LCC Percent Deltas for First Follow Destroyer and Corvette PEM Fuel-Cell Powered Variant

	Cost Percent Deviation From Respective Baseline			
	PEM Fuel-Cell Powered Variant*			
Ship Type	SbSSP	DRSSP	DiSSP	DRPP
Destroyer	0.6%	2.9%	4.6%	4.4%
Corvette	N/A	-0.3%	1.5%	1.5%

*1. Fuel cell stacks replaced at five year intervals (five change-outs)

2. A rate of 4.5% was used to discount cumulative LCCs to net present value (NPV) LCCs.

3. First follow Baseline Destroyer LCC is estimated at a NPV of 647 million dollars (FY$93).

4. First follow Baseline Corvette LCC is estimated at a NPV of 257 million dollars (FY$93).

4.3.3.3 Basic Construction Cost Impacts

Fuel cell technology impacts on ship cost is best demonstrated from cost deltas at the BCC level of detail. Each Variant has a Baseline Propulsion and/or Electric Plant modified by Fuel Cell systems. The "Balance

of Ship" (includes those ship systems not in the Propulsion and Electric Plants), typically changes in weight, volume and specification requirements in order to "balance" those design changes introduced by fuel cells. Table 4-5 defines BCC, and Appendix F provides a more detailed explanation of BCC.

Replacement of Destroyer Baseline systems with PEM fuel cell systems results in Variants having higher BCCs than the Baseline. These BCC increases are attributed to the combination of more costly PEM systems and more costly "Balance of Ships". Corvette Variant BCCs are estimated to have a lower cost than the Corvette Baseline for the ship service (DRSSP) and propulsion (DRPP) alternatives. These BCC decreases are attributed to more simplified Electric Plants and Balance of Ship size reductions.

The impact of replacement costs for the Baseline Propulsion and Electrical Systems by PEMFCs are summarized in Table 4-7. For each ship application, the figures provided in Appendix G demonstrate the effects of SWBS 200 and 300 cost deltas on the "Balance of Ship" and total BCC cost deltas. These figures also highlight the cost impacts of major Baseline and Variant systems/subsystems on the Propulsion Plant, Electric Plant, "Balance of Ship" and total BCC.

Table 4-7

PEM Fuel Cell Cost Impacts for Baseline Propulsion Plant, Electrical Plant (SWBS 200 and SWBS 300, Respectively) and Balance of Ship

Application	Cost Impact (% Higher Than Baseline)						Comments	
	Propulsion Plant		Electric Plant		Balance of Ship			
	Destroyer	Corvette	Destroyer	Corvette	Destroyer	Corvette	Destroyer	Corvette
Standby Ship Service Power Variant	<1%	-	<1%	-	<1%	-	Negligible Cost Increase	-
Ship Service Power Variant	2%	>-1%	5%	>-1%	6%	-2%	Cost Increase	Negligible Cost Decrease
Distributed Ship Service Power Variant	2%	<1%	5%	1%	13%	1%	Cost Increase	Cost Increase
Propulsion Power Variant	10%	7%	<1%	-3%	-4%	-8%	Propulsion Plant Cost Increase Electric Plant Cost Decrease	Propulsion Plant Cost Increase Electric Plant Cost Decrease

4.3.3.4 Fuel Cell System Costs

All fuel cell system costs assume a mature technology in fiscal year 2010. Learning has then already progressed significantly on the technology so that production emulates that of modern Navy technologies.

Fuel cell stack cost estimates are derived from commercially land-based, natural gas-powered designs. Design differences between commercial and US Navy stacks are predicted to be nominal, unless significant design changes are necessary to meet shock and vibration resistance. Therefore, stack cost estimates are not expected to vary significantly between commercial and U.S. Navy applications.

All BOP cost estimates reflect BOPs designed to consume only Navy diesel fuel and sized specifically for US Navy ships, i.e., BOPs on US Navy ships have a higher packing factor than land-based BOPs. The BOP designs were modified to process Navy diesel fuel, instead of a less complex chemical, natural gas.

At all given power ratings, the requirement to process a more complex diesel fuel drives "diesel-type" BOP costs higher than those costs for "natural gas-type" BOPs.

Figure 4-19 illustrates the average cost per kilowatt for Baseline ship power systems and fuel cell systems. The average cost of an "Existing System" is 500 dollars per kilowatt. All proposed fuel cell systems, except MC plants, have an average cost per kW which is at least 90% higher than an "Existing System". MC plants are projected to have nearly the same average cost per kilowatt as an "Existing System", but MC plants were also found generally less attractive due to their low power density.

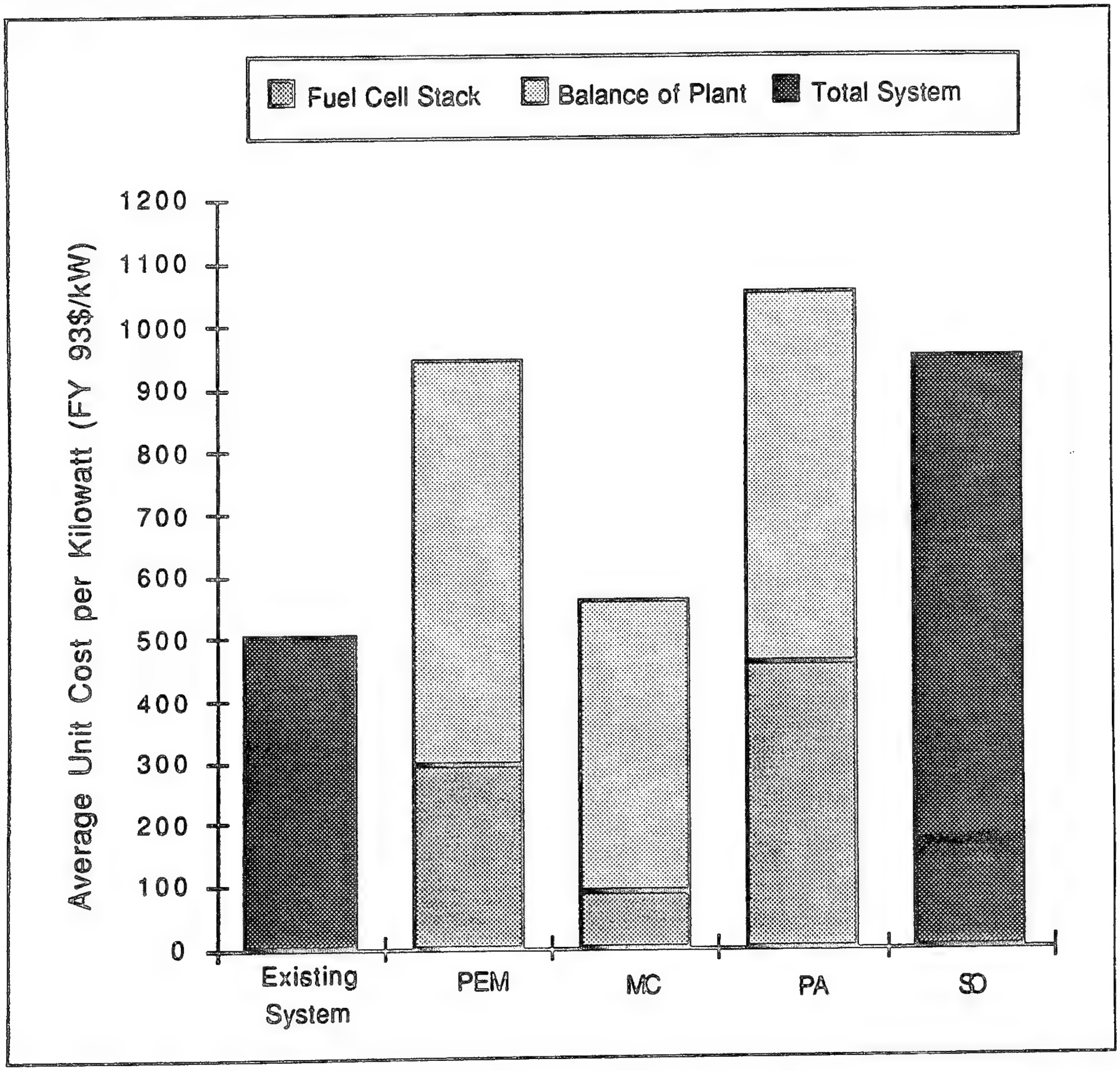

Figure 4-19. Estimated Average Cost Per Kilowatt for an Existing Power System and for Proposed Fuel Cell Systems*

*"Existing System" represents the average cost of baseline power systems.

A comparison matrix, which combines average estimated fuel cell system costs with qualitative technical risk, serves as a useful preliminary tool in prioritizing desirable fuel cell systems. This comparison, shown in Table 4-8, suggests that conventional baselines are the optimum choice when considering only qualitative risk and cost; PEM systems still present the best combination of potential and risk among the fuel cell variants. Although SO systems are projected to be cost competitive with PEM fuel cell systems, PEM systems are preferred because they are in later stages of RDT&E. MC and PA plants are the least desirable options due to a combination of higher acquisition cost and considerably higher weights and volumes than the other fuel cell options. Their higher weights and volumes prevent overall ship size reductions and minimize overall ship cost savings.

Table 4-8

Average Cost Per Kilowatt and Risk Estimates for an Existing Power System and Proposed Fuel Cell Systems

Type	$/kW	Relative Risk	General Cost Observations & Other Observations	Explanation of Risk
Existing Baseline Systems: e.g., Diesel or Standby Generators (Conventional)	500	Lowest	This example represents the highest average cost per kilowatt of all ship baseline machinery & electric applications considered to be replaced by fuel cell systems	These systems have been successfully used on Navy ships for the past 30 years. Technical and cost risks are minimal; Costs are based on historical information.
Proton Exchange Membrane: Total Fuel Cell System Run at 6 Atmospheres	946	High	Average cost is nearly double that of conventional-type systems	Have not been tested for high-powered applications (>5 MW); Have not been run successfully on Navy diesel fuel nor to Navy specifications. Undefined propulsion/electric control systems.
Phosphoric Acid: Total Fuel Cell System	1051	Lowest of Fuel Cell Options	Average cost per kilowatt is about 20% higher than PEM fuel cell systems. Has larger volume and weight than PEM at same power which offsets potential improvements in ship design and cost impacts.	Commercially used for high-powered land-based applications (>5 MW); Have not been run successfully on Navy diesel fuel nor to Navy specifications. Undefined propulsion/electric control systems.
Molten Carbonate: Total Fuel Cell System Run at 6 Atmospheres	560	Medium	Average cost per kilwatt is very competitive with present day baseline machinery and electrical systems. Current systems operating at 1 atm have low power density. Long term operation at 6 atm not demonstrated.	Have not been tested for high-powered applications (>5 MW); Have not been run successfully on Navy diesel fuel nor to Navy specifications. Undefined propulsion/electric control systems.
Planar Solid Oxide: Total Fuel Cell System	951	Highest of Fuel Cell Options	High level of technical & cost uncertainty Has the least amount of data available Has the highest power density. Cost competitive with PEM fuel cell systems.	Nearly the same technical risk as PEM but in earlier stages of R&D. Have not been run successfully on Navy diesel fuel nor to Navy specifications. Undefined propulsion/electric control systems.

For all proposed fuel cell systems, the primary cost driver was the balance of plant (BOP), ranging from an average 56 to 84% of the system cost; the fuel cell stacks range from an average 16 to 44% of the system cost. No breakouts were calculated for the solid oxide fuel cell systems. Some sources suggest the assembly labor drives the cost of the BOP while materials drive the cost of fuel cell stacks (Reference 3). The BOP percentage variation with power level for PEM systems is illustrated in Appendix H, Figure

1a. Similar trends for the molten carbonate systems and phosphoric acid systems can be observed in Appendix H, Figures 1b, 1c and 1d.

4.3.3.5 Cost Issues

Operating and Support (O&S) Costs

The recommended O&S scenario suggests replacing PEM fuel cells five times over a 30-year ship life combined with annual replenishment of zinc oxide beds which remove sulfur from the fuel. This recommended O&S scenario for fuel cell systems causes a significant O&S cost increase relative to the respective Baselines, up to 12% for direct DRPP applications. The net present value LCCs for the Variants following this fuel cell "maintenance" scenario are shown in Figures 4-20 and 4-21. Figures 4-20 and 4-21 also depict the LCC trend for each Variant with alternative O&S profiles. These alternative scenarios require fewer change-outs of fuel cell stacks and/or sulfur removal equipment over the life of each ship. This equates to less material and labor, reducing the overall O&S cost and thereby decreasing the LCC.

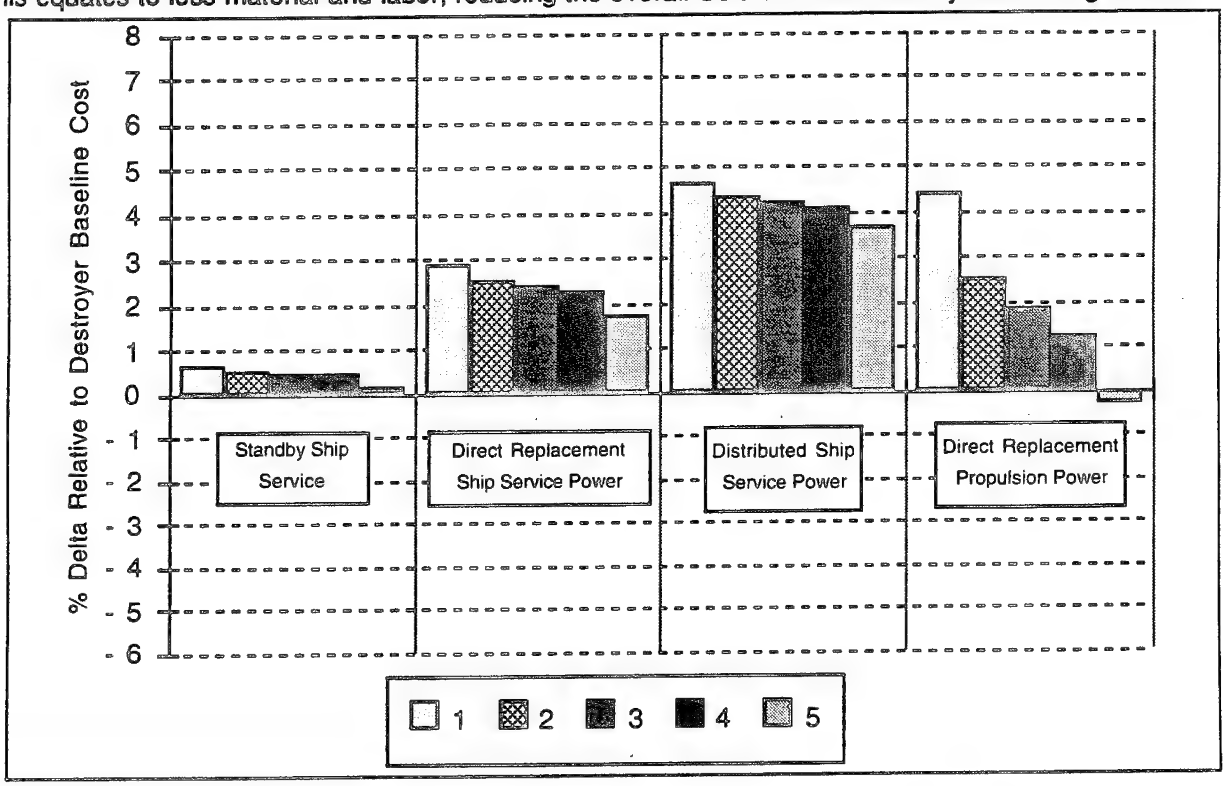

Figure 4-20. First Follow Destroyer Life Cycle Cost (LCC) Percent Deltas for Five O&S Scenarios Using PEM Fuel Cell Systems*

Five Assumed O&S Scenarios Proposed for 30 Year Ship Life:

1. Baseline: Fuel cell stacks replaced at 5 year intervals (5 change-outs), annual zinc oxide bed replenishment
2. Fuel cell stacks replaced at 10 year intervals (2 change-outs), annual zinc oxide bed replenishment
3. Fuel cell stacks replaced at 15 year intervals (1 change-out), annual zinc oxide bed replenishment
4. Fuel cell stacks never replaced over 30 year ship life, annual zinc oxide bed replenishment
5. Fuel cell stacks and zinc oxide sulfur removal bed never replaced over 30 year ship life.

*A rate of 4.5% was used to discount cumulative LCCs to net present value (NPV) LCCs.

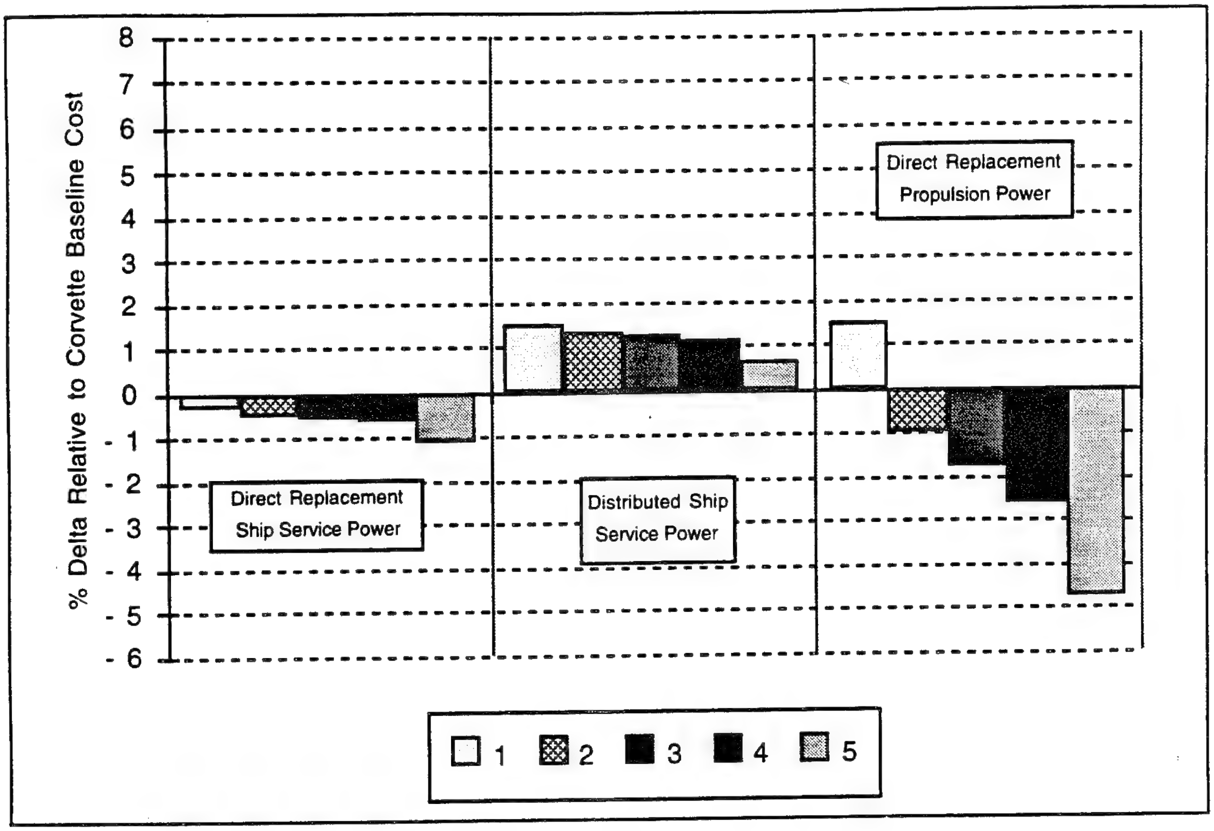

Figure 4-21. First Follow Corvette Life Cycle Cost (LCC) Percent Deltas for Five O&S Scenarios Using PEM Fuel Cell Systems

First follow baseline Destroyer LCC is estimated at a NPV of 647 million dollars (FY93).
The effects of reducing LCC by having fewer fuel cell stack replacements are most pronounced for the DRPP Variant. The high powered fuel-cell stacks associated with the DRPP Variants are considerably more expensive to replace over the ship life than the stacks required in the other ship Variants. More specifically, for the DRPP Variant, the Destroyer has 36 MW of stacks and the Corvette has 20 MW of stacks. Both sets of these stacks would be much more costly to replace every five years than, for example, the stacks from the Destroyer's direct ship service replacement Variant at 7.5 MW power.

For all PEM fuel-cell powered ships, fuel economy was noticeably improved relative to the respective Baseline ships. Fuel costs were estimated to comprise less than 6% of each Baseline's LCC. The more economical fuel-cell powered Variant ships reduce these fuel costs by a little more than an additional 1% of the Baseline's LCC. Therefore, fuel economy is presently not a source for significant O&S cost savings. O&S cost categories are identified in Tables F.3 and F.4 of Appendix F.

Unknown Costs

"Unknown Costs" may very well be the principal cost issue. Unaddressed technical issues must first be resolved so applicable costs can be estimated. For example, additional items may be needed to process fuel and generate power, and systems may need to be customized for Navy shipboard usage. Once the costs of these unknowns are estimated and added to existing estimates, ship LCC observations highlighted in this study may show a considerable increase.

Technical unknowns expected to be significant cost drivers are fuel cell control system components. New control system designs, likely to be introduced by fuel cell technologies, must consider parameters like fluid

control and system interface with fuel cell stacks. These parameters may require more specialized power control systems within each ship's propulsion and electrical system, and cost estimates for these systems must be addressed.

According to reports from the Power Systems Department, Code 82, CDNSWC, fuel cell systems are quieter than Baseline systems. Requirements for various noise reducing materials and equipment throughout each Variant ship will likely be less. The improved quieting performance of fuel cell systems for each Variant could reduce the costs presently associated with quieting each Baseline.

The increase in US Navy environmental regulations may result in an acquisition and O&S cost increase for Baseline prime movers. Environmental regulations, such as reducing emissions from Baseline prime movers, may increase Baseline ship costs while Variant ships, having fuel cell systems which may already meet future emission regulations, may not have any cost increase. For example, additional systems may be required to suppress harmful emissions, special machinery may be required to clean each system or each system must be "scrubbed" of harmful pollutants more frequently. The Power Systems Department, Code 82, suggests that by operating "cleaner", fuel cell systems eliminate the need for many of the current steps required to meet environmental regulations.

Destroyer Versus Corvette Cost Estimates

It is strongly recommended to use caution when comparing the costs, cost deltas and cost percent deltas between the Destroyer and Corvette Variants. The outcome of each are based on different design philosophies and assumptions:

Two different ship design tools were used by two different organizations: (1) the Advanced Surface Ship Evaluation Tool (ASSET), developed and used by the Navy, for all Destroyer concepts and (2) an in-house ship synthesis model, developed and used by BLA, Inc., for all Corvette concepts. While both design tools generate feasible ship designs, design assumptions may vary slightly between these ship design tools.

Power system technologies for the Destroyer and Corvette baselines are clearly dissimilar. Destroyer Variant costs are measured relative to a Destroyer Baseline with future, more efficient, systems that are more expensive than corresponding Destroyer systems employed in current Navy fleets. These "future" Destroyer Baseline systems, e.g., ICR Gas Turbines, Electric Propulsion Generators and Permanent Magnet Motors, consume less fuel. This mitigates the ship impact of Destroyer Baseline-to-PEM Variant design transitions, reflecting less dramatic technical and cost deltas than those for the Corvette PEM Variants. Corvette Variant costs are measured relative to a Corvette Baseline with less efficient, CODOG-related systems used in current Navy fleets. Power system related changes are more pronounced for the Corvette Baseline-to-PEM Variant design transitions, reflecting more distinctive technical and cost deltas from PEM fuel cell replacement.

According to the Naval architects involved in this study, design variations from the Destroyer Baseline to the Destroyer Variants are more conservative than those design variations from the Corvette Baseline to its Variants. As expected, cost impacts parallel design alteration impacts. The Corvette Variants show less cost penalty than the Destroyer Variants for the same system substitution study: more Baseline systems are downsized or removed from the Corvette Variants, reducing the Baseline ship weight by as much as 20%. These less conservative ship-level changes help to counteract the positive cost deltas caused by installing the more costly PEM fuel cell plants, i.e., more costly than the Baseline systems they are replacing.

Finally, a cost delta percent for a Destroyer is very different than that for a Corvette. For example, a 2% deviation from a Destroyer LCC Baseline is about 13 million dollars; a 2% deviation from a Corvette LCC Baseline is about 5 million dollars.

Cost Deltas for Distributed Ship Service Power

For both the Destroyer and Corvette, costs for the DiSSP Variant are presently being compared to Baselines with traditional combatant ship service arrangements, i.e., modern ship service power sources, such as diesel generators, are not distributed in zones throughout the ship. Therefore, a more reasonable cost delta for this particular application would reflect the cost of each DiSSP Variant relative to the cost of each Baseline having DiSSP arrangements.

4.3.4 Conclusions

1. All ship Variants have somewhat higher O&S costs than their respective Baselines. Present fuel cell system maintenance (replacing PEM stacks five times over the ship life and annual replacement of sulfur-removal beds) causes a significant O&S cost increase of Variants relative to their respective Baselines.

2. Alternative fuel-cell O&S profiles, having less frequent change-outs, show a notable trend in the reduction of ship O&S and LCCs.

3. PEM fuel cell systems show smaller cost impacts for Corvette.

4. Ship cost impacts are proportional to PEM system size.

5. O&S estimates for all Variants reveal that improved fuel economy has minimal impact on LCC savings, no greater than 2% of the Baseline LCC estimates.

6. For all proposed fuel cell systems, except solid oxide, the primary cost driver was the balance of plant (BOP), ranging from an average 56 to 84% of the system cost. Cost drivers are not yet identified for the solid oxide fuel cell systems.

7. Reports indicate that labor and overhead are cost drivers for the BOP, and materials are cost drivers for fuel cell stacks.

8. Although not yet quantified, the cost uncertainty for the Baseline Destroyer's Integrated Power System is significantly higher than that of the Baseline Corvette's CODOG system.

9. The characteristics and estimated costs of shipboard power control systems for each Variant have not yet been determined.

10. Improved quieting performance of fuel cell systems for each Variant may reduce the costs presently associated with quieting each Baseline ship (same conclusion applies to other signatures as well).

11. The positive cost delta of fuel cell systems versus Baseline systems may decline over the next several years due to the potential cost increase of Baseline systems from environmental regulations projected for the near future.

12. The Destroyer Baseline is propelled by an Integrated Power System which is more "futuristic" than the Corvette Baseline's CODOG system. Incorporation of a unconventional Integrated Power System mitigates the ship impact for each Destroyer Baseline-to-PEM Variant design transition. This mitigated Destroyer Variant design impact results in cost impacts less dramatic than those for each Corvette PEM Variant.

13. Design changes to the Destroyer Baseline were more conservative than those for the Corvette Baseline. These less-conservative ship design changes for the Corvette help to counteract the extra costs incurred from more costly PEM systems and, therefore, the Corvette Variant costs portray more optimistic estimates than Destroyer Variant costs.

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CHAPTER 5

PRELIMINARY STRATEGY FOR FUEL CELL DEVELOPMENT

5.1 Establish the Goal

This study has shown that fuel cells can provide benefits in military effectiveness without major changes in the displacement of a ship and cost. Even though the impact upon the ship (regarding displacement, power, size) may not necessarily always be positive, and even though some cost increase may result, it was found that significant benefits would result from reduced signatures, reduced toxic emissions, and reduced fuel consumption. Similar conclusions were found by the Department of Energy (DOE) for land based applications, and prompted them, in February 1993, to issue a National Program Plan for Fuel Cells in Transportation.

The key objective of the DOE plan is, and the Navy Plan should be, to carry out research, development and commercialization of fuel cells so as to provide, as rapidly as possible, economic competitors to internal combustion engines.

Specific issues that have been identified in this study and need to be addressed in the development of fuel cell technology for Navy use are listed in Table 5-1.

Table 5-1

Specific Issues for Navy Applications of Fuel Cells

• High Power Density (kW/lb)
• Shock/Damage Tolerance
• Diesel Fuel Compatibility/Fuel Reforming
• Sulfur Tolerance
• Marine Contaminants
• Start-Up Time/Number of Starting Cycles
• Sudden Load Release/Electrical Load Dynamics
• Stack Life (For 30 Years Service Life)

The DOE Transportation and Navy combatant applications share the following needs:

- They require high power density.
- Rapid start up and dynamic load following is required.
- Decreased material costs and improved designs are required.

The DOE Program for development of fuel cells for transportation involves concurrent emphasis on relatively short-term, low-risk technologies (e.g., PA fuel cells in buses) and long-term high-risk technologies (e.g., PEM and SO fuel cells in automobiles and other applications).

The key objectives of the DOE program are to establish:

- The technology potential for fuel cell automobiles by mid-decade, with fleet demonstrations underway shortly after the year 2000.

- The technical basis for heavy duty vehicles by mid-decade, with the commercialization process underway by late in the decade.

- The use of alternative fuels (methanol, ethanol, natural gas and liquified natural gas).

In order for the Navy to share the development costs of fuel cell plants that have high power density and that use diesel fuel, it is essential to find common ground with other land-based applications. The useful power for transportation applications ranges from 50 - 100 kW for cars, 200 to 500 kW for trucks and 1 - 3 MW for trains. Navy ship-service power requirements range from 250 kW to 3 MW. The Navy should also leverage all applicable ARPA developments.

Navy Objectives: Since fuel cells are modular and small plants provide the same efficiency characteristics as large plants, it is proposed that the Navy objectives be to:

- Demonstrate fuel cells plants in the 200-500 kW range operating on diesel fuel.

- Demonstrate the 200-500 kW plants (operating on diesel fuel) for auxiliary power on small combatants or propulsion power on small boats, or auxiliary vessels.

- Develop 3 MW class fuel cell power plants for ship-service power on destroyer sized combatants.

- Develop multiple (10 to 20) MW Size Propulsion Plants for combatants and "dual use" vessels (e.g., oilers and sealift ships).

The goal can therefore be set for useful and practical power plants to be used on board Navy vessels as shown in Table 5-2.

Table 5-2

Goals for Future Navy Fuel Cell Plants

Power Plant Size: Ships Service: 200 - 500 kW initially; 3 MW future. Propulsion: 10 MW Plant **Weight-to-Power Ratio**: 5-20 lb/kW* **Specific fuel consumption**: 0.3-0.5 lb/kWh* **Density**: Not less than 20 lb/ft^3. **Exhaust Temperature**: Not to exceed 500 (350 goal) degrees Fahrenheit **Fuel**: Diesel fuel Marine (DFM)
*The weight to power ratio and the specific fuel consumption should be set as shown in Figure 5-1 to obtain benefits in all applications. For example, if the weight-to-power ratio is high, a low fuel consumption will be required to compensate.

Note that the goals stated above are preliminary since goals for fuel cell development should be established after finding a consensus with the requirements for ground transportation and any military base uses envisioned.

5.2 Establish Milestones

In order to achieve the stated goals, the strategy must focus on defining intermediate steps. The intermediate steps are those matching the various power levels mentioned above for use in land based applications:

50 - 100 kW for use in cars.
200 - 500 kW for use in trucks.
1 - 3 MW for use on trains.

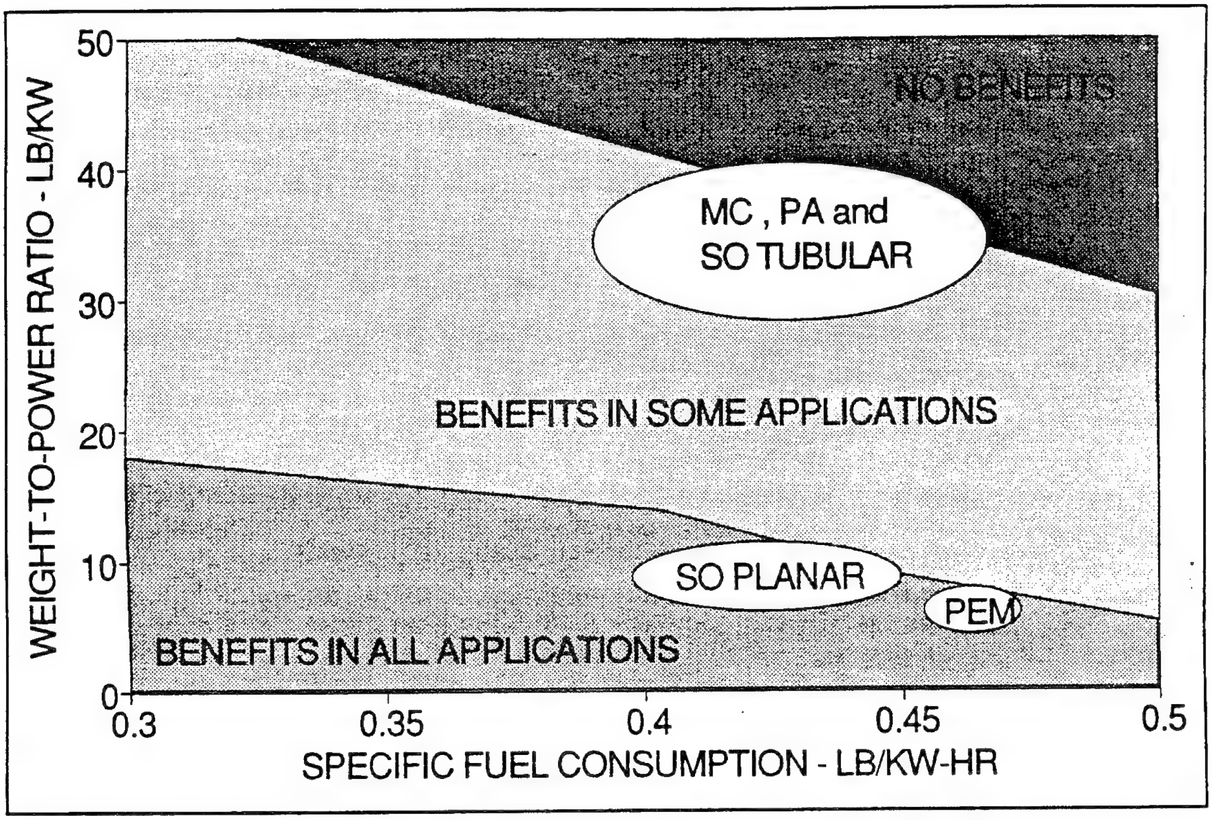

Figure 5-1. Weight and Fuel Consumption Targets

At the same time, the following marine uses may be found for these plants.

50 - 100 kW:	-	Auxiliary power for patrol boats (USCG Cutters)
	-	Propulsion power for small test craft (demonstrators)
200 - 500 kW:	-	Auxiliary power for small combatants
	-	Propulsion power for small boats, auxiliary vessels, or fast planing vessels.
1 - 3 MW:	-	Auxiliary power for combatants, and cruise ships.
	-	Propulsion power for small vessels such as MCM,TUGS, auxiliary vessels and fishing vessels.
10 MW:	-	Propulsion power for combatants and "dual-use" vessels. The goal is to use the same stacks as in 1-3 MW plants (in order to avoid the development of Navy-specific stacks).

5.2.1 Development Steps

The proposed steps are as follows:

(A) Develop and fabricate a technology demonstration plant in the 250 - 500 kW range with the characteristics as listed in Section 5.1. This could be a joint program with DOE or ARPA. At least two plants (one DOE/ARPA and one Navy) should be manufactured; more if a large scale demonstration is desired.

(B) Evaluate the technology demonstration plant (250 - 500 kW) in the laboratory.

(C) Develop a prototype plant in the 250 - 500 kW range designed to meet Navy requirements, perform qualification tests, and evaluate on board a ship.

(D) Develop and manufacture a 3 MW plant with the desired characteristics and install on a ship for evaluation.

(E) Develop 10-MW class power plants for propulsion applications.

(F) Go to full scale production for Navy, maritime, and land-base uses.

For the plants above, there is no need to specify the type of plant preferred. Industry should be allowed to come up with the answer and a natural selection process be permitted to eliminate those fuel cell types that cannot meet the goals. The preferred size of the technology demonstration plant should be determined after coordination with Navy users and sponsors as well as ARPA and DOE.

Some specific test craft that should be considered for use are:

- The AMT model (44 ft planing craft powered by 2 X 300 hp engines and two waterjets)
- The MK3 patrol boat being currently fitted with permanent magnet motors (65 ft, 1 X 1500 hp gas turbine generator, two PM motors)
- Navy Chase Boat (35 ft with twin inboard diesel engines)

These craft are currently being used in other CDNSWC programs but should be available for future fuel cell power plant evaluations.

In steps A and B, more than one plant type should be developed so that various technologies can be evaluated.

The Navy should also, in parallel with the above, evaluate such plants as the ONSI 200 kW Phosphoric Acid (PA) plant, to determine operating characteristics such as response time, and to demonstrate compatible interfaces between a fuel cell plant and a DC power distribution system. The Annapolis Detachment of CDNSWC is currently under consideration as a test site for one of these plants.

Other specific R&D, such as demonstrating a suitable sulfur removal system for shipboard service applications and developing sulfur tolerant fuel cell technology, must also be supported as a necessary part of the Navy effort.

In addition, ship impact studies should be continued to evaluate other ship applications and to consider the merits of using a bottoming cycle with a high temperature fuel cell.

5.3 Establish a Schedule

5.3.1 Fuel Cell Development

A tentative schedule to develop fuel cells in accordance with the proposed steps of Section 5.2 is:

A.	250 - 500 kW Technology Demonstration Plants:	1996
B.	Laboratory Evaluation:	1997-98
C:	Prototype 250 - 500 kW Plant Development:	1998-2001
	At-Sea Evaluation:	2002-2003
D.	3 MW Prototype Plant Development:	2002-2005
	At-Sea Evaluation	2006-2008
E.	10 MW Propulsion Plant Development	2005-2012
F.	Production:	
	250 - 500 kW Plants	2005
	3000 kW Plants	2010
	10000 kW Propulsion Plants	2015

5.4 FY-94 Efforts

As a result of this study, several areas of interest manifested themselves in which further ship impact studies might yield very promising results. The following is a list of these possibilities.

1. Evaluate the ship impact of using low-power-density, high-efficiency fuel cells on non-combatant vessels ("dual use" ships).

2. Study the ship impact of using high temperature fuel cells with bottoming cycles. Such a system is being considered for a submarine application.

3. Conduct a cost assessment of the four fuel cell technologies in a DDG-51 backfit in which the GT SS generators are replaced.

4. Examine the pay-offs of using easily reformed types of fuel or sulfur-free fuel in fuel cells.

5. Examine the pay-offs of using a fuel cell plant designed to a specific duty cycle (take advantage of overload capability) as opposed to a power level.

6. Investigate the sulfur tolerance of SOFCs.

7. Investigate the full potential of an optimized (fuel type, size, risk, cost, cell type, weight, etc.) fuel cell plant in an optimal (ship type, mission type, plant type) naval application. For instance, a U.S. coastal patrol craft with access to various types of fuel or a remote-controlled application in which hydrogen and oxygen can be carried as fuel (very efficient and stealth). This study would be on a first order level and would help bring "current" fuel cell technology into immediate applications in the naval arena.

8. Investigate the impact on baselines of conforming to stricter emission standards.

NSWC hopes to receive a 200 kW PA power plant in FY95 at no cost under a Congressionally directed program. NSWC plans to utilize the availability of this 200 kW power plant to evaluate load response and interfaces with a DC power distribution system.

5.5 Funding Synergies

The strategy should rely heavily on finding synergies with other users. This may mean that compromises will have to be worked out but it is essential for new technologies to justify a "dual-use" compatibility in order to support our industrial base and minimize DOD costs. To satisfy this requirement, discussions and participation in DOE and ARPA programs is essential. This effort should involve joint technical support and funding.

Because fuel cells are friendly to the environment, and require no additional equipment to comply with current or future regulations, there exists strong government support for their development. The National Science Foundation, which has operating bases in the Antarctic region has a real need for non-polluting, efficient power plants. Other Government agencies such as the U.S. Coast Guard and NOAA are under pressure to be "clean" in atmospheric pollution terms. These result from requirements of the Clean Air Act of 1991 and the California Air Resources Board. Other states, e.g, the State of Maryland, which passed legislation for reducing the pollution of the Chesapeake Bay by the turn of the century, are also beginning to take actions, similar to California. In response to that pressure, currently, the cruise ship industry is considering the use of fuel cells to curb air and water pollution, while they are in port.

It is recommended that the Navy become an active participant in putting together a coalition of Government and Private Funding support for maritime fuel cell development based on environmental and military benefits. Fuel cells may be the only viable method of meeting future environmental regulations at a reasonable cost.

CHAPTER 6

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LIST OF FUEL CELL MANUFACTURERS

Allied Signal Aerospace Company
2525 West 190th Street, P.O. Box 2690
Torrance, CA 90509-2960
Mr. Richard Gibson
310-512-3310

Analytic Power Corporation
208 Summer Street
S. Boston, MA 02210
Mr. David Bloomfield
617-542-6352

Energy Research Corporation
3 Great Pasture Road
Danbury, CT 06813
Mr. Sandy Abens
203-792-1460

Giner, Inc.
14 Spring Street
Mr. Jose Giner
Mr. Anthony LaConte
617-899-7270

International Fuel Cells
P.O. Box 739
South Windsor, CT 06074
Mr. Donald McVay
203-727-2384

M-C Power Corporation
8040 S. Madison Street
Burr Ridge, IL 60521
Mr. Thomas C. Benjamin
708-986-8040

Technology Management Inc.
9718 Lake Shore Boulevard
Cleveland, OH 44108
Mr. Benson Lee
216-541-1000

Westinghouse Electric Corporation
1310 Beulah Road
Pittsburgh, PA 15235-5098
Mr. Emerson R. Ray
412-256-2125

APPENDIX A

FUEL CELL CHARACTERIZATION DATA

Table A-1. Baseline Power Plants

	Propulsion	Propulsion	Ships Service	Ship Service
Power System	GE LM2500 GT	ICR Gas Turbine With Generator	CAT 3412 Diesel Generator Set	Allison 501 K-34 Gas Turbine Generator Set
Power, kW	19,575 (Shaft)	21,600 DC	425 AC	2500 AC
lb/kW	3.02	6.8	20.13	26.88
Cu Ft/kW	0.12	0.26	0.46	0.47
Footprint, FT^2	231	358	43	167.4
Height, Ft	10	15.8	5	7
Fuel	DFM	DFM	DFM	DFM
Fuel Consumption lb/kWh				
125% Load	N/A	N/A	N/A	N/A
100% Load	0.48	0.48	0.556	0.720
50% Load	0.557	0.46	0.526	1.047
25% Load	0.704	0.54	0.587	1.198

Table A-2

Power System Matrix – General Characteristics/PEMFC Technology Status

Power System Type	Proton Exchange Membrane (PEM) Fuel Cells
Manufacturers	Energy Partners Ballard Power Systems Giner, Inc. International Fuel Cells Analytic Power Corporation Siemens
Design Features and Operating Characteristics	May use Nafion or Dow membrane Good Delta–P capability High cells/inch Water Balance Critical Short Startup time
Operating Temperature	35 to 250 degrees Fahrenheit
Operating Pressure	1 to 6 Atm
Fuel Compatability	Hydrogen preferred CO is a poison Desulfurization required Stacks have been run on methanol
Fuel Reforming Internal External	 No due to low temperature Yes
Status of Technology	Several 5 to 10 kW stacks delivered Several transportation demonstrations planned (93–97)
Largest Plant, kW	34 kW in Single Stack (Siemens)
No. of Plants Built	IFC (2) Ballard (est 20, 4 to 10 kW syacks) Analytic Power (1, 10 kW, 25 W stacks) GE (est 20) Siemens (Several 5 kW Stacks, and 34 kW Power Plants)
Proven Life	Siemens: 20,000 hr on 540 sq cm cell at 540 ASF & 0.7V. 5 microvolts/cell hr loss, similiar results on 20 cell 1180 sq cm stack Ballard: >1000 hrs on 5 to 10 kW stacks, 7 microvolts/hr loss on 3600 hr single cell test General Electric: 3200 hr on 1.1 sq. ft. cell with 1 microvolt/hr loss 57,000 hr on 4 cell 0.38 sq ft H2–O2 stack
Other Applications	15 kW UUV (94); 40 kW Car (94); 120 kW Bus (93) 34 kW Submarine Power (92); 60 kW Car (97) 20 KW Marine Power Plant (Vickers) Canadian 300 kW Sub Power Plant

Table A-3

General Characteristics/MCFC Technology Status

Power System Type	Molten Carbonate (MC) Fuel Cell
Manufacturers	Energy Research Corporation (ERC) M-C Power Corporation (MCPC) International Fuel Cells Hitachi IHI
Design Features	Electrodes and electrolyte matrix manufactured using a tape casting, drying and sintering process. Nobel metal catalyst not required. Requires CO2 in cathode stream. Nickel oxide cathode currently limits life at pressure. Limited start-ups due to thermal stress. Requires 0.2 to 0.3 inches per cell.
Operating Temperature	1150 to 1250 F
Operating Pressure	1 to 6 Atm
Fuel Compatibility	CO is a fuel (reacts with steam to form H2). Commercial plants use natural gas or coal derived fuel. Desulfurization required. Can operate on wide variety of fuels.
Fuel Reforming Internal External	 Yes, both directly or indirectly. ERC uses indirect reformer plates. Yes. ERC operated on EXXSOl D110 (a heavy liquid fuel using an external methonator and internal reformer plates.
Status of Technology	State-of-the-art manufacturing processes. Stack manufacturing costs are in affordable range for electric utilities. Full area, full height stacks. Up to 60% efficiency if combined with bottoming cycle. 100 kW to 2 MW demonstrations in 93/94.
Largest Plant Built	100 to 250 kW stacks. Demos up to 2 MW planned in 94.
Number of Plants Built	ERC: Several 4 ft^2 stacks; 234 cell 70 kW plant; 6 ft^2 stacks in 1994. MCPC: 20 kW (10 ft^2); 250 kW planned in 1994.
Proven Life	ERC: 10,000 hrs on 4 ft^2 stacks. MCPC: 2500 hrs on 10 ft^2 stacks (10,000 hrs planned). IFC: 5000 hrs on 1 ft^2 stack.
Other Applications	On-site commercial - natural gas. Industrial cogeneration - natural gas/by-product gases. Electric utility dispersed. Electric utility base load and repowering.

Table A-4

Power System Matrix - General Characteristics/PAFC Technology Status

Power System Type	Phosphoric Acid Fuel Cells
Manufacturers	US Fuel Cell Manufacturing Co. International Fuel Cells/ONSI Westinghouse H-Power Fuji Mitsubishi Toshiba
Design Features	Liquid electrolyte in silicon carbide matrix. CO2 rejecting electrolyte. External manifolds, mostly heat treated carbon and graphite construction. Teflon used as a binder and for wetting control.
Operating Temperature	350 to 450 F
Operating Pressure	1 to 8.2 atmospheres demonstrated.
Fuel Compatibility	Operated on natural gas and naphtha. Desulfurization required. CO can be tolerated up to 4%.
Fuel Reforming	Can operate on externally reformed fuels.
Status of Technology	Commercial 200 kW natural gas plants in production phase. Plants to 11 MW demonstrated. >100 PAFC plants field tested. Over 100,000 hours field operation on 200 kW plants with >90% operational availability.
Largest Plant, kW	11 MW plant with 10 sq ft cells.
No. of Plants Built	IFC: >170 plants from 12.5 kW to 11 MW. Westinghouse: Numerous stacks from 2.5 to 375 kW.
Proven Life	IFC: 12,448 hrs with <1 mv/1000 hrs degradation. IFC: A 200 kW plant has operated 7050 hrs. Westinghouse: >15,000 hrs with <8 mv/1000 hrs degradation.
Other Applications	On-site power. Electrical and gas utility applications. Bus power.

Table A-5

Power System Matrix - General Characteristics/SOFC Technology Status

Power System Type	Phosphoric Acid Fuel Cells
Manufacturers	Westinghouse (W) Allied Signal (AS) Technology Management, Inc. (TMI)
Design Features	Cathode - Strontium - doped Lanthanum magnanite Electrolyte - Yttria - stabilized Zirconia Anode - Nickel metal stabilized Zirconia Interconnect - doped Lathanum chromite Active cell thickness < 2 mm Tubular design is air cooled & normally operates with 4 to 7 excess air.
Operating Temperature	1832 F (1000 C) with extensive research to lower to 700 to 800 C.
Operating Pressure	Demonstrated at 1 atm, but operation up to 30 atm appears feasible. Pressure effects currently being characterized.
Fuel Compatibility	Less sensitive to contaminants due to high temperature and solid electrolyte. CO is consumed as a fuel.
Fuel Reforming	Internal reforming of methane has been demonstrated. High grade heat is available for either external or internal reforming.
Status of Technology	Power plant of 1152 cells (50 cm) demonstrated. Tubular cell lengths of 200 cm fabricated. Operating power density for tubular cells 320 to 415 mW/sq cm. AS cells: 900 mW/sq cm on cells with ultrathin (<10 micometer) electrolyte. AS experience limited to cells to 10 cm x 10 cm due to sealing and interconnect problems in stacks. Argonne National Laboratory is developing sealants with good results. TMI is developing a planar cell without co-sintering of cell components. Performance goal for the TMI cells is 100 mW/sq cm.
Largest Plant, kW	W: 25 kW rated (44 kW peak); 100 kW plant in 95; MW units in 96/97. AS plans a 100 watt stack demonstration in December 1993.
No. of Plants Built	W: (4) 3-kW plants, (3) 25-kW plants. Allied Signal: 2 cell stack (100 sq cm).
Proven Life	Allied Signal: 1000 hr with little degradation. W: 40,000 hrs on 1989 vintage cells; 2590 hrs including four cold starts on 25 kW plant containing 1152 50 cm cells. 7000 hrs on a 20 kW fuel test unit. Westinghouse life goal is 50,000 - 100,000 hr life. Westinghouse degradation rate: <1%/1000 hrs at constant current.
Other Applications	Tubular Technology aimed at Electrical and Gas Utility Applications. Tubular Technology being considered for submarine propulsion. Planar Technology has potential application in transportation applications requiring high power density.

Table A-6

PEM Technology Fuel Cell Systems - Corvette Propulsion

Nominal Power, MWatt		9			10			11		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	9043.79	9043.72	9043.71	10047.64	10047.63	10047.63	11053.49	11054.5	11053.51
Air Flow	SCFS	286.26	267.18	250.48	318.04	296.83	296.83	349.87	326.5781	306.1398
Exhaust Flow	SCFS	299.12	279.18	261.73	332.32	310.17	310.17	365.59	341.2514	319.8949
Exhaust Temp	Deg. F.	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150	150
Sea H2O	GPM	1495.12	1395.44	1308.22	1661.08	1550.34	1550.34	1827.36	1705.69	1598.95
Potable H2O	GPM	8.64	8.07	7.56	9.60	8.96	8.96	10.56	9.86	9.24
Cost: Fuel Cell	$ / kW	265.20	312.34	387.88	265.19	312.34	312.34	265.18	312.33	387.89
: BOP	$ / kW	359.57	362.76	346.93	351.00	354.44	354.44	343.56	347.21	358.71
Fuel Cell Wt	Ltons	7.12	8.40	10.44	7.91	9.33	9.33	8.70	10.27	12.76
Fuel Cell Vol	Cu. Ft	759.48	895.61	1113.68	843.77	995.14	995.14	928.16	1094.86	1361.29
BOP Wt	Ltons	13.20	12.61	11.99	14.16	13.52	13.52	15.10	14.41	13.80
Desulfurizer Wt	Ltons	1.39	3.89	3.65	4.63	4.33	4.33	5.10	4.76	4.46
BOP Vol	Cu. Ft.	695.38	665.58	620.41	743.96	711.70	711.70	791.40	756.80	725.91
Desulfurizer Vol	Cu. Ft.	163.85	178.79	167.62	212.82	198.64	198.64	234.13	218.54	204.87
Fuel, 125%	Lb\kW-hr	0.4804	0.4631	0.4460	0.4804	0.4631	0.4631	0.4804	0.4631	0.4460
100%	Lb\kW-hr	0.4633	0.4507	0.4377	0.4633	0.4507	0.4507	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4509	0.4418	0.4321	0.4509	0.4418	0.4418	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4451	0.4388	0.4316	0.4451	0.4388	0.4388	0.4451	0.4388	0.4316
25%	Lb\kW-hr	0.4585	0.4542	0.4491	0.4585	0.4542	0.4542	0.4585	0.4542	0.4491

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-7

PEM Fuel Cells - Corvette Ship System Generator

Nominal Power, kWatt		400			500			600		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	401.94	401.94	401.94	502.43	502.43	502.43	602.91	602.91	602.91
Air Flow	SCFS	12.72	11.87	11.13	15.90	14.84	13.92	19.08	17.81	16.70
Exhaust Flow	SCFS	13.29	12.41	11.63	16.62	15.51	14.54	19.94	18.61	17.45
Exhaust Temp	Deg. F.	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00
Sea H2O	GPM	66.45	62.02	58.14	83.06	77.52	72.68	99.67	93.03	87.21
Potable H2O	GPM	0.38	0.36	0.34	0.48	0.45	0.42	0.58	0.54	0.50
Cost: Fuel Cell	$ / kW	265.87	312.98	388.50	265.79	312.91	388.41	265.72	312.84	388.37
: BOP	$ / kW	871.01	860.53	859.18	799.89	791.59	792.19	746.98	740.30	742.36
Fuel Cell Wt	Ltons	0.32	0.37	0.46	0.40	0.47	0.58	0.48	0.56	0.70
Fuel Cell Vol	Cu. Ft	33.77	39.89	49.58	42.24	49.77	61.90	50.71	59.74	74.32
BOP Wt	Ltons	1.81	1.74	1.68	2.06	1.98	1.91	2.29	2.20	2.12
Desulfurizer Wt	Ltons	0.37	0.37	0.37	0.23	0.22	0.20	0.28	0.26	0.24
BOP Vol	Cu. Ft.	84.83	81.36	78.26	97.38	93.28	89.60	109.35	104.62	100.42
Desulfurizer Vol	Cu. Ft.	17.02	17.02	17.02	10.64	9.93	9.31	12.77	11.92	11.17
Fuel, 125%	Lb\kW-hr	0.4804	0.4631	0.4460	0.4804	0.4631	0.4460	0.4804	0.4631	0.4460
100%	Lb\kW-hr	0.4633	0.4507	0.4377	0.4633	0.4507	0.4378	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4509	0.4418	0.4321	0.4509	0.4418	0.4321	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4444	0.4381	0.4309	0.4444	0.4381	0.4309	0.4452	0.4388	0.4316
25%	Lb\kW-hr	0.4577	0.4534	0.4483	0.4577	0.4534	0.4483	0.4577	0.4534	0.4483

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-8

PEM Technology Fuel Cell Systems - Destroyer Propulsion Fuel Cell System

Nominal Power, MWatt		16.20			18.00			19.80		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	16278.74	16278.75	16278.76	18087.59	18087.57	18087.49	19896.17	19896.35	19896.16
Air Flow	SCFS	515.27	480.92	450.86	572.52	534.35	500.95	629.77	587.7895	551.0468
Exhaust Flow	SCFS	538.13	502.26	470.87	597.93	558.07	523.46	657.72	614.1989	575.8059
Exhaust Temp	Deg. F.	150	150	150	150	150	150	150	150	150
Sea H2O	GPM	2691.2	2511.79	2354.8	2990.25	2790.89	2616.43	3289.22	3069.99	2878.06
Potable H2O	GPM	15.56	14.52	13.61	17.28	16.13	15.12	19.01	17.74	16.64
Cost: Fuel Cell	$ / kW	265.16	312.32	387.89	265.16	312.33	387.83	265.14	312.29	387.8
: BOP	$ / kW	316.44	320.86	333.05	309.81	314.42	326.74	304.06	308.82	321.30
Fuel Cell Wt	Ltons	12.82	15.12	18.8	14.24	16.8	20.89	15.66	18.48	22.97
Fuel Cell Vol	Cu. Ft	1366.93	1612.19	2004.77	1518.87	1791.41	2227.45	1670.61	1970.53	2450.13
BOP Wt	Ltons	19.65	18.74	17.93	21.67	20.15	19.28	23.1	22.06	20.59
Desulfurizer Wt	Ltons	7.42	6.92	6.49	8.24	7.69	7.3	9.07	8.57	8.03
BOP Vol	Cu. Ft.	1022.53	976.21	935.01	1111.38	1047.93	1003.66	1179.43	1129.83	1070.33
Desulfurizer Vol	Cu. Ft.	340.64	317.93	298.06	378.49	353.26	335.23	416.34	393.34	368.75
Fuel, 125%	Lb\kW-hr	0.4633	0.4631	0.446	0.4804	0.4631	0.446	0.4804	0.4631	0.4461
100%	Lb\kW-hr	0.4529	0.4507	0.4377	0.4633	0.4507	0.4377	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4463	0.4418	0.4321	0.4509	0.4418	0.4321	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4465	0.4388	0.4316	0.4451	0.4388	0.4316	0.4451	0.4388	0.4316
25%	Lb\kW-hr	0.4686	0.4542	0.4491	0.4585	0.4542	0.4491	0.4585	0.4542	0.4491

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-9

PEM Fuel Cells - Destroyer Ship Service Generator

Nominal Power, kWatt		2250			2500			2750		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	2260.93	2260.93	2260.93	2512.14	2512.14	2512.14	2763.36	2763.35	2763.36
Air Flow	SCFS	71.57	66.79	62.62	79.52	74.22	69.58	87.47	81.64	76.53
Exhaust Flow	SCFS	74.78	69.80	65.43	83.09	77.55	72.70	91.40	85.30	79.97
Exhaust Temp	Deg. F.	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00	150.00
Sea H2O	GPM	373.78	348.86	327.06	415.31	387.62	363.39	456.84	426.38	399.74
Potable H2O	GPM	2.16	2.02	1.89	2.40	2.24	2.10	2.64	2.46	2.31
Cost: Fuel Cell	$ / kW	265.40	312.54	388.07	265.37	312.51	388.05	265.36	312.49	388.04
: BOP	$ / kW	489.12	489.72	498.41	473.10	474.18	483.28	459.26	460.74	470.22
Fuel Cell Wt	Ltons	1.78	2.10	2.61	1.98	2.33	2.90	2.18	2.57	3.19
Fuel Cell Vol	Cu. Ft	189.85	223.90	278.47	211.01	248.83	309.42	232.09	273.67	340.37
BOP Wt	Ltons	5.36	5.14	4.94	5.72	5.48	5.27	6.07	5.81	5.58
Desulfurizer Wt	Ltons	1.04	0.97	0.91	1.16	1.08	1.01	1.27	1.19	1.12
BOP Vol	Cu. Ft.	269.03	257.65	247.58	287.52	275.23	264.31	305.55	292.34	280.64
Desulfurizer Vol	Cu. Ft.	47.89	44.70	41.90	53.21	49.66	46.56	58.53	54.63	51.21
Fuel, 125%	Lb\kW-hr	0.4804	0.4631	0.4460	0.4804	0.4631	0.4460	0.4803	0.4630	0.4460
100%	Lb\kW-hr	0.4633	0.4507	0.4377	0.4633	0.4507	0.4377	0.4633	0.4507	0.4377
75%	Lb\kW-hr	0.4509	0.4418	0.4321	0.4509	0.4418	0.4309	0.4509	0.4418	0.4321
50%	Lb\kW-hr	0.4451	0.4388	0.4316	0.4451	0.4388	0.4316	0.4451	0.4388	0.4316
25%	Lb\kW-hr	0.4585	0.4542	0.4491	0.4585	0.4542	0.4491	0.4585	0.4542	0.4490

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-10

MC Fuel Cells - Corvette Propulsion

Nominal Power, MWatt		0.8	0.8	0.8	0.9	0.9	0.9	1	1	1
Cell Design Voltage		0.65	0.7	0.75	0.65	0.7	0.75	0.65	0.7	0.75
Net Power	kWatts	8000	8000	8000	9000	9000	9000	10000	10000	10000
Air Flow	SCFS	331.49	314.17	302.67	372.93	353.44	340.50	414.38	392.71	378.33
Exhaust Flow	SCFS	335.50	317.98	306.32	377.43	357.73	344.61	419.37	397.48	382.91
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	2713.1	2463.8	2300.9	3052.3	2771.5	2588.5	3391.4	3079.3	2876.1
Fuel Cell Wt	Ltons	111.75	125.29	5280.14	125.71	140.95	165.36	139.68	156.61	183.74
Fuel Cell Vol	Cu. Ft	4106.54	4605.22	5402.46	4619.85	5180.75	6077.67	5133.15	5756.28	6752.88
BOP Wt	Ltons	24.99	23.86	22.17	27.79	26.48	24.70	30.59	29.09	27.22
Desulfurizer Wt	Ltons	7.44	7.37	7.46	8.24	8.17	8.26	9.05	8.96	9.06
BOP Vol	Cu. Ft.	1433.30	1285.45	1326.25	1562.90	1403.68	1436.77	1692.50	1521.92	1547.28
Desulfurizer Vol	Cu. Ft.	510.50	507.71	516.26	564.98	561.83	570.90	619.47	615.95	625.53
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	473.81	512.67	470.41	474.59	512.67	470.41	475.36
Fuel, 125%	Lb\kW−hr	0.6236	0.6236	0.6236	0.6236	0.5859	0.5525	0.6236	0.5859	0.5525
100%	Lb\kW−hr	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206
75%	Lb\kW−hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW−hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW−hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-11

MC Fuel Cells - Corvette Ship Service Power

Nominal Power, MWatt		0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
Cell Design Voltage		0.65	0.7	0.75	0.65	0.7	0.75	0.65	0.7	0.75
Net Power	kWatts	300	300	300	400	400	400	500	500	500
Air Flow	SCFS	12.43	11.80	11.35	16.58	15.73	15.13	20.72	19.66	18.92
Exhaust Flow	SCFS	12.58	11.93	11.49	16.78	15.91	15.32	20.97	19.88	19.14
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	101.7	94.2	86.2	135.6	125.0	114.9	169.5	155.8	143.7
Fuel Cell Wt	Ltons	4.23	4.70	262.26	5.63	6.26	7.35	7.02	7.83	12.59
Fuel Cell Vol	Cu. Ft	154.08	173.64	203.34	205.41	231.19	270.86	256.74	288.74	338.38
BOP Wt	Ltons	3.45	3.72	2.71	3.73	3.98	2.97	4.01	4.24	3.22
Desulfurizer Wt	Ltons	1.24	1.24	1.30	1.32	1.32	1.38	1.40	1.40	1.46
BOP Vol	Cu. Ft.	435.42	375.03	475.26	448.38	386.85	486.32	461.34	398.68	497.37
Desulfurizer Vol	Cu. Ft.	90.97	91.02	95.59	96.42	96.43	101.05	101.87	101.84	106.51
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	467.80	512.67	470.41	467.88	512.67	470.41	467.96
Fuel, 125%	Lb\kW-hr	0.6236	0.6236	0.6236	0.6236	0.5859	0.5525	0.6236	0.5859	0.5525
100%	Lb\kW-hr	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206
75%	Lb\kW-hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW-hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW-hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-12

MC Fuel Cells - Destroyer Propulsion

Nominal Power, MWatt		16	16	16	18	18	18	20	20	20
Cell Design Voltage		0.65	0.7	0.75	0.65	0.7	0.75	0.65	0.7	0.75
Net Power	kWatts	16000	16000	16000	18000	18000	18000	20000	20000	20000
Air Flow	SCFS	662.98	628.32	605.33	745.85	706.86	681.00	828.72	785.40	756.67
Exhaust Flow	SCFS	670.99	635.96	612.65	754.87	715.45	689.23	838.74	794.95	765.81
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	5426.3	4925.7	4601.9	6104.6	5541.2	5177.1	6782.9	6156.6	5752.4
Fuel Cell Wt	Ltons	223.46	250.58	10560.20	251.38	281.90	330.73	279.31	313.23	368.80
Fuel Cell Vol	Cu. Ft	8212.99	9209.46	10804.15	9239.61	10360.52	12154.57	10266.22	11511.58	13504.99
BOP Wt	Ltons	47.38	44.78	42.38	52.98	50.02	47.44	58.57	55.25	52.49
Desulfurizer Wt	Ltons	13.88	13.74	13.87	15.49	15.33	15.47	17.10	16.92	17.07
BOP Vol	Cu. Ft.	2470.07	2231.34	2210.39	2729.26	2467.81	2431.42	2988.45	2704.28	2652.46
Desulfurizer Vol	Cu. Ft.	946.37	940.65	953.33	1055.34	1048.88	1062.59	1164.31	1157.11	1171.86
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	480.04	512.67	470.41	481.60	512.67	470.41	483.16
Fuel, 125%	Lb\kW-hr	0.6236	0.6236	0.6236	0.6236	0.5859	0.5525	0.6236	0.5859	0.5525
100%	Lb\kW-hr	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206
75%	Lb\kW-hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW-hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW-hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-13

MC Fuel Cells - Destroyer Ship Service Power

Nominal Power, MWatt		2.3	2.3	2.3	2.5	2.5	2.5	2.7	2.7	2.7
Cell Design Voltage		0.65	0.7	0.75	0.65	0.7	0.75	0.65	0.7	0.75
Net Power	kWatts	2300	2300	2300	2500	2500	2500	2700	2700	2700
Air Flow	SCFS	95.30	90.34	87.02	103.59	98.19	94.58	111.88	106.05	102.15
Exhaust Flow	SCFS	96.46	91.42	88.07	104.84	99.37	95.73	113.23	107.32	103.38
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	780.0	709.7	661.4	847.8	771.2	719.0	915.6	832.8	776.5
Fuel Cell Wt	Ltons	32.16	36.02	1428.28	34.95	39.15	45.93	37.74	42.28	49.61
Fuel Cell Vol	Cu. Ft	1180.70	1324.70	1553.76	1283.36	1439.80	1688.80	1386.02	1554.91	1823.85
BOP Wt	Ltons	9.04	8.95	7.77	9.60	9.47	8.27	10.16	10.00	8.78
Desulfurizer Wt	Ltons	2.85	2.83	2.90	3.01	2.99	3.06	3.17	3.15	3.22
BOP Vol	Cu. Ft.	694.61	611.50	696.30	720.53	635.15	718.40	746.45	658.80	740.51
Desulfurizer Vol	Cu. Ft.	199.94	199.25	204.85	210.84	210.07	215.78	221.73	220.90	226.71
Cost: Fuel Cell	$ / kW	80.66	90.14	106.11	80.66	90.14	106.11	80.66	90.14	106.11
: BOP	$ / kW	512.67	469.92	467.57	512.67	470.41	467.57	512.67	470.41	467.57
Fuel, 125%	Lb\kW−hr	0.6236	0.6236	0.6236	0.6236	0.5859	0.5525	0.6236	0.5859	0.5525
100%	Lb\kW−hr	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206	0.4606	0.4366	0.4206
75%	Lb\kW−hr	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244	0.4652	0.4438	0.4244
50%	Lb\kW−hr	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275	0.5921	0.5579	0.5275
25%	Lb\kW−hr	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960	1.0990	0.9874	0.8960

NOTE: Based on a pressure of 6.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-14

PA Technology Fuel Cell Systems - Corvette Propulsion

Nominal Power, MWatt		9			10			11		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	8610.87	8610.87	8610.87	9567.64	9567.63	9567.64	10524.40	10524.40	10524.40
Air Flow	SCFS	255.74	238.69	223.77	284.15	265.21	248.63	312.57	291.73	273.50
Exhaust Flow	SCFS	268.19	250.31	234.66	297.99	278.12	260.74	327.79	305.93	286.81
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	1905.70	1677.91	1478.60	2117.44	1864.34	1642.88	2329.19	2050.78	1807.17
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.32	458.03	754.77	320.32	458.03	754.76	320.31	458.02	754.76
: BOP	$ / kW	488.21	500.18	558.30	482.83	494.06	556.02	476.41	491.83	550.51
Fuel Cell Wt	Ltons	57.75	82.61	136.19	64.16	91.79	151.32	70.59	100.96	166.46
Fuel Cell Vol	Cu. Ft	4190.17	5994.22	9882.14	4655.35	6660.12	10980.16	5121.71	7326.01	12078.17
BOP Wt	Ltons	31.57	29.01	27.79	34.12	31.09	30.61	35.93	33.74	31.65
Desulfurizer Wt	Ltons	6.97	6.97	6.97	7.48	7.48	7.48	7.97	7.97	7.97
BOP Vol	Cu. Ft.	1834.44	1731.55	1672.82	1939.65	1824.94	1783.95	2021.68	1931.43	1844.36
Desulfurizer Vol	Cu. Ft.	341.67	341.67	341.67	366.95	366.95	366.95	391.48	391.48	391.48
Fuel, 125%	Lb\kW-hr	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

NOTE: Based on a pressure of 8.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-15

Corvette 2100 Ship System Generator

Nominal Power, kWatt		400			500			600		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	382.71	382.71	382.71	478.38	478.38	478.38	574.06	574.06	574.06
Air Flow	SCFS	11.37	10.61	9.95	14.21	13.26	12.43	17.05	15.91	14.92
Exhaust Flow	SCFS	11.92	11.12	10.43	14.90	13.91	13.04	17.88	16.69	15.64
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	84.70	74.57	65.72	105.87	93.22	82.14	127.05	111.86	98.57
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.61	458.31	755.03	320.58	458.27	755.00	320.55	458.25	754.98
: BOP	$ / kW	868.08	870.80	919.24	813.40	818.12	867.79	776.15	782.01	831.62
Fuel Cell Wt	Ltons	2.57	3.68	6.05	3.22	4.60	7.57	3.86	5.52	9.08
Fuel Cell Vol	Cu. Ft	186.54	266.83	439.21	233.77	334.13	549.01	279.82	400.24	658.81
BOP Wt	Ltons	4.15	4.03	3.66	4.59	4.31	4.19	4.97	4.81	4.63
Desulfurizer Wt	Ltons	0.80	0.80	0.79	0.94	0.94	0.93	1.07	1.07	1.06
BOP Vol	Cu. Ft.	308.17	299.71	268.30	340.44	318.68	310.64	366.38	355.95	343.42
Desulfurizer Vol	Cu. Ft.	38.99	38.89	38.79	45.72	45.58	45.46	52.07	51.91	51.77
Fuel, 125%	Lb\kW-hr	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

NOTE: Based on a pressure of 8.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-16

PA Technology Fuel Cell Systems - Destroyer Propulsion

Nominal Power, MWatt		16.20			18.00			19.80		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.75	0.75	0.80
Net Power	kWatts	15499.50	15499.50	15499.50	17221.67	17221.67	17221.66	18943.83	18943.83	18943.83
Air Flow	SCFS	460.33	429.64	402.79	511.47	477.38	447.54	562.62	525.11	492.29
Exhaust Flow	SCFS	482.74	450.56	422.40	536.38	500.62	469.33	590.01	550.68	516.26
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	3430.27	3020.25	2661.48	3811.41	3355.83	2957.20	4192.55	3691.42	3252.92
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.30	458.01	754.75	0.45	458.00	754.74	320.29	458.00	754.74
: BOP	$ / kW	458.62	474.56	533.50	320.29	469.21	529.19	448.42	464.18	524.43
Fuel Cell Wt	Ltons	103.94	148.70	245.13	453.55	165.22	272.37	127.03	181.73	299.60
Fuel Cell Vol	Cu. Ft	7542.07	10790.07	17786.68	115.48	11988.44	19763.10	9217.43	13186.82	21739.53
BOP Wt	Ltons	48.99	45.77	41.68	8379.16	48.97	45.84	56.19	51.78	48.48
Desulfurizer Wt	Ltons	10.33	10.33	10.33	52.98	11.10	11.10	11.84	11.84	11.84
BOP Vol	Cu. Ft.	2537.09	2410.74	2264.62	11.10	2542.12	2419.64	2827.18	2663.32	2533.49
Desulfurizer Vol	Cu. Ft.	509.80	509.80	509.80	2693.65	547.95	547.95	584.97	584.97	584.97
Fuel, 125%	Lb\kW-hr	3.9582	3.9285	3.9025	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	3.9582	3.9285	3.9025	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	3.9582	3.9285	3.9025	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	3.9582	3.9285	3.9025	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

NOTE: Based on a pressure of 8.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-17

Destroyer Ship Service Generator

Nominal Power, kWatt		2250			2500			2750		
Cell Design Voltage		0.70	0.75	0.80	0.70	0.75	0.80	0.70	0.75	0.80
Net Power	kWatts	2152.72	2152.72	2152.72	2391.91	2391.91	2391.91	2631.10	2631.10	2631.10
Air Flow	SCFS	63.93	59.67	55.94	71.04	66.30	62.16	78.14	72.93	68.37
Exhaust Flow	SCFS	67.05	62.58	58.67	74.50	69.53	65.18	81.95	76.48	71.70
Exhaust Temp	Deg. F.	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00	300.00
Sea H2O	GPM	476.42	419.48	369.65	529.36	466.09	410.72	582.30	512.69	451.79
Potable H2O	GPM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cost: Fuel Cell	$ / kW	320.41	458.12	754.85	320.40	458.11	754.84	320.40	458.10	754.83
: BOP	$ / kW	587.04	597.72	653.78	577.22	587.89	645.43	566.76	579.70	636.60
Fuel Cell Wt	Ltons	14.45	20.66	34.06	16.04	22.96	37.83	17.65	25.25	41.62
Fuel Cell Vol	Cu. Ft	1048.43	1499.44	2471.13	1164.13	1665.91	2745.04	1281.02	1832.39	3020.13
BOP Wt	Ltons	10.52	9.62	9.24	11.16	10.36	10.11	11.73	11.07	10.46
Desulfurizer Wt	Ltons	2.87	2.87	2.87	3.06	3.06	3.06	3.25	3.25	3.25
BOP Vol	Cu. Ft.	762.31	694.98	669.45	806.91	749.86	730.65	846.87	799.52	754.38
Desulfurizer Vol	Cu. Ft.	136.51	136.51	136.51	146.09	146.09	146.09	155.39	155.39	155.39
Fuel, 125%	Lb\kW-hr	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680	0.6237	0.5940	0.5680
100%	Lb\kW-hr	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899	0.4456	0.4159	0.3899
75%	Lb\kW-hr	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402	0.3959	0.3662	0.3402
50%	Lb\kW-hr	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896	0.5453	0.5156	0.4896
25%	Lb\kW-hr	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245	1.0802	1.0505	1.0245

NOTE: Based on a pressure of 8.0 atm and 0.5% sulfur diesel fuel.
Sulfur absorber equipment designed for 24 hrs/cycle, for 90 days.

Table A-18

All SOFC Power Plant Performance Summary, 56 Modules
Westinghouse: 5004 Cells/Module, 150 cm Length

	Rated Power 20 MW	Peak Power 40 MW
LNG Flow, lb/s	1.60	4.09
Fuel Utilization, %	90	90
Air Utilization, %	25	25
Net DC Power, MW	21.6	44.3
Gross AC Power, MW	20.5	42.5
Air Blower, MW	0.3	2.1
Fuel Blower, MW	0.2	0.4
Net AC Power, MW	20.1	40.0
Plant Heat Rate, BTU/kWh	6758	8632
Plant Volume, cu ft/kW	26	13
Fuel Cell Stack, lb/kW	56.4	25.2
Air Flow, lb/s	1.18	0.59
Exhaust Flow, lb/s	98.03	249
Exhaust Temperature, F	99.64	254
Plant Cost, $/kW	586	768
	2945	1945

Table A-19

SOFC/Combustion Turbine Power Plant
(Westinghouse Data)

Key Design Parameters	
No. of SOFC Modules	24
Turbine Inlet Temperature, Degs C	983
Turbine Pressure Ratio	10:1
SOFC Fuel Utilization, %	90
SOFC Air Utilization, %	25
SOFC System Performance	
LNG Flow, lb/S	1.53
Net DC Power, MW	17.5
Net AC Power, MW	16.6
Air Blower, MW	0.1
Fuel Blower, MW	0.2
Turbine System Performance	
LNG Flow, lb/S	0.49
Fuel Compressor, MW	0.1
Net AC Power, MW	3.6
Plant, Net AC MW	20.1
Plant Heat Rate, BTU/kWh	8511

Table A-20

Preliminary Planar SO Fuel Cell Characteristics

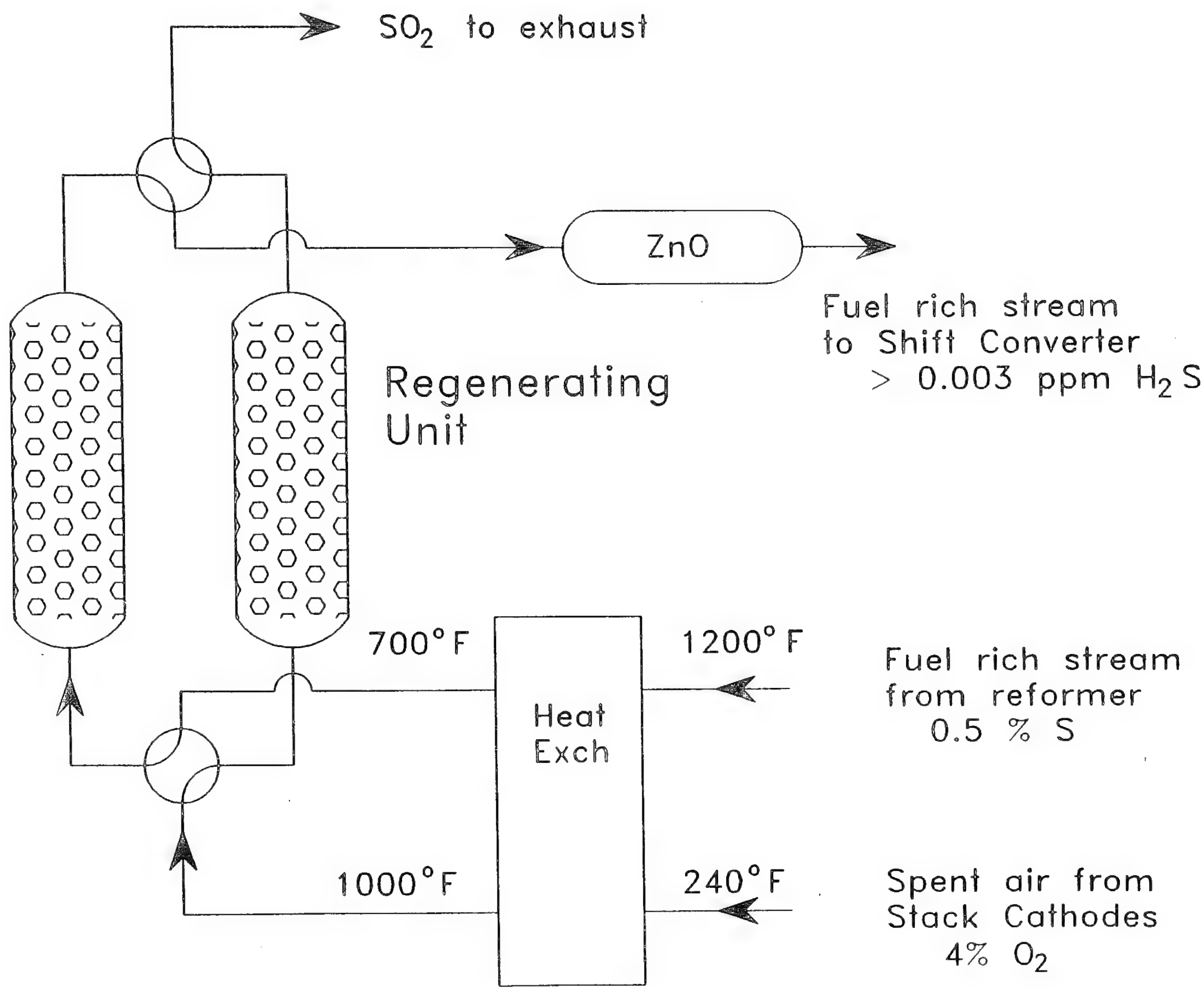
	Technology Management Inc.			Allied Signal	
	300 kW	10,000 kW	10,000 kW Combined Cycle	10 kW	50 kW
Weight, lb/kW	11.7	8	8	13.5	9.57
Volume, cu ft/kW	0.66	0.35	0.35	0.54	0.144
Fuel Consumption, lb/kWh					
125%	0.63	0.63	0.5		
100%	0.42	0.42	0.3	0.31	0.31
75%	0.36	0.36	0.3		
50%	0.34	0.34	0.3		
25%	0.32	0.32	0.29		
Cost, $/kW	<1000	<1000	<1000		
Operating Temperature, C	1000	1000	1000	1000	1000
Air Flow, SCF/lb Fuel	360				
Exhaust Flow, SCV/lb Fuel	375				
Seawater Flow, gal/lb Fuel	1.0				
Exhaust Temperature, F	130				
Cold Start Time, 3 Hours	3				

NOTES:

1. Allied Signal data based on 400 mA/sq cm performance.
2. All data preliminary.
3. No sulfur removal equipment included.

Figure A-21

REGENERATIVE SULFUR ADSORBER BED



APPENDIX B

POLLUTANT REQUIREMENTS

Figure B-1.

Engine and Fuel Cell NO_x Emissions and the California Air Resources Board (CARB) Limits

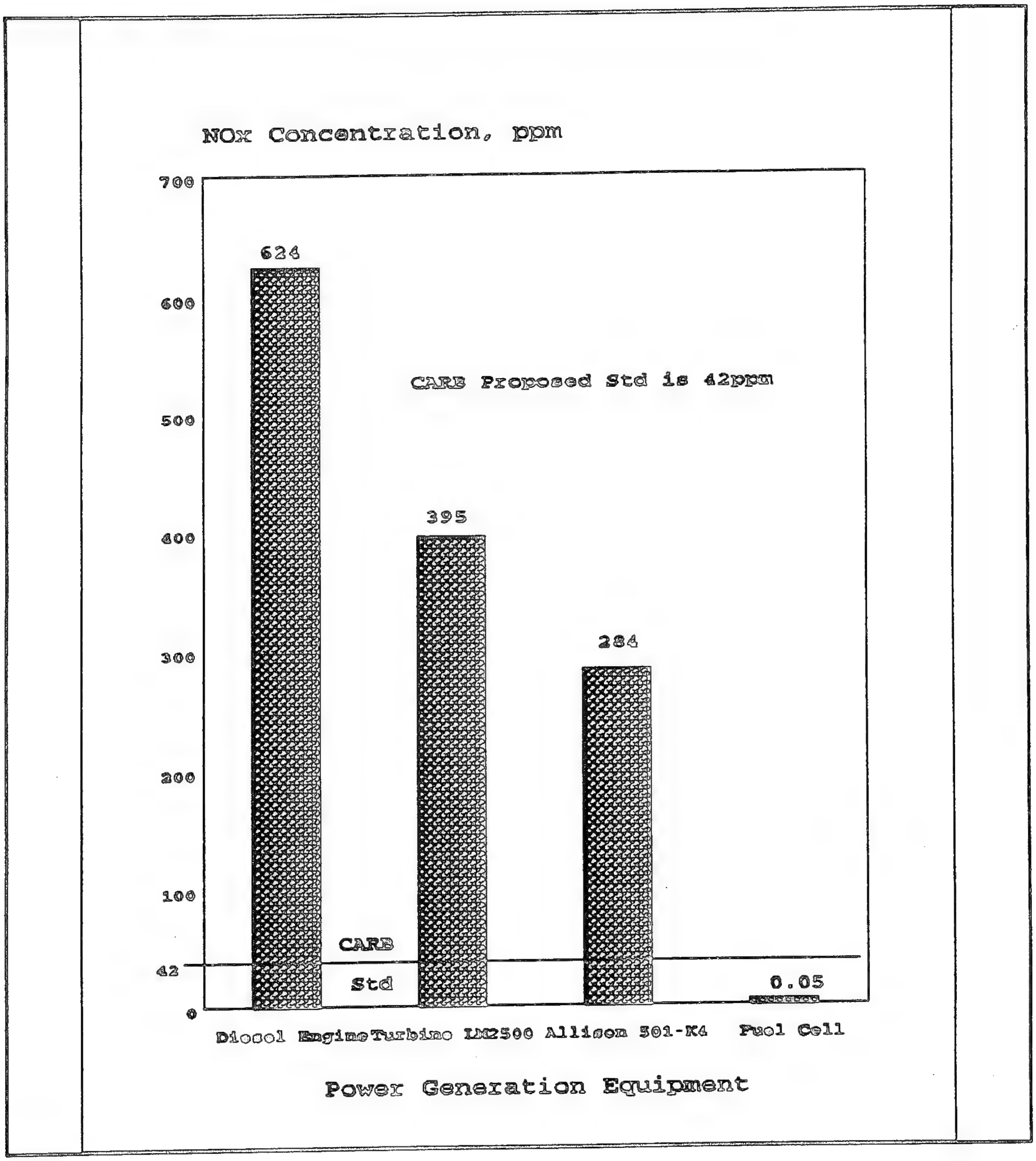
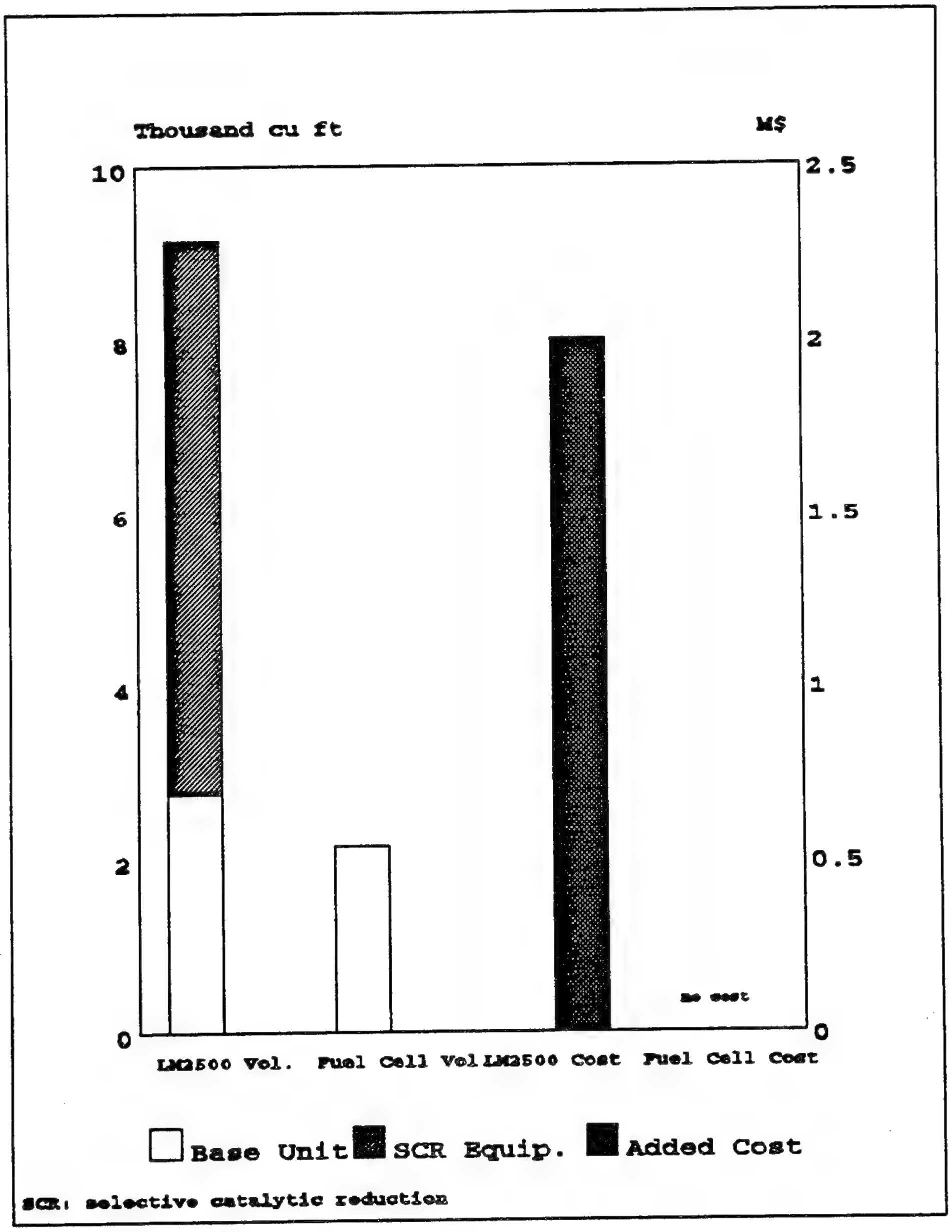


Figure B-2.

Impact of the Proposed CARB NO_x Emissions Standard on the Size and Cost of Marine Power Plants



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APPENDIX C

CORVETTE, SHIP IMPACT, ADDITIONAL INFORMATION

1.0 INTRODUCTION

The objective of this task is to define a corvette-size combatant to allow quick intervention in remote places around the world. It is intended that this design be used as a baseline to assess the ship impact of fuel cell technology.

The Corvette 2100 is dedicated to surface warfare missions and is expected to face a threat from mainly third-world/developing countries.

The Corvette 2100 is meant to be a small combatant (corvette size) that will provide an affordable alternative to a frigate or destroyer. However, it is not intended to replace these large combatants which will remain more capable in terms of range, payload and seakeeping, but to provide a complementary capability at a more reasonable cost.

2.0 MISSION NEED

2.1 Mission Requirements

2.1.1 Primary Missions

- Anti-surface warfare operations in limited scale conflicts.
- Shore bombardment in support of landing operations.
- Deployment in conjunction with a task force, or alone, as early-crisis intervention vessel.

2.1.2 Secondary Missions

- Conduct and support anti-terrorist and/or commando operations.
- Anti-air self defense against aircraft (helicopters) and against missiles (to include electronic warfare).
- Anti-submarine self defense against conventional (diesel) submarines.
- EEZ patrol.
- Pollution control.

Note that EEZ patrol and pollution control missions are not normally U.S. Navy missions, but were considered as means of making the best use of the Corvette 2100 in peacetime.

2.2 Theater of Operations

Anywhere around the world. Potential conflicting zones are:

- Middle East (Persian Gulf - Mediterranean Sea)
- Indonesia - India (Indian Ocean)
- Korea
- China - Taiwan (China Sea)
- Yugoslavia (Adriatic Sea)
- Black Sea
- South America - Central America
- Etc.

The Corvette 2100 may be prepositioned near the potential theaters of operations in order to allow a quick intervention in its primary role of crisis containment. Should the policy of the U.S. Navy favor the regrouping of its fleet within the U.S. territory, the Corvette 2100 would be deployed together with resupply vessels up to an appropriate distance from the theater of operations or would resupply in friendly ports before carrying out its mission.

2.3 Threat

The seaborne threat shall be mainly constituted by modern corvettes/frigates with limited, but sophisticated weapons (long range surface-to-surface missiles such as EXOCET, HARPOON, OTOMAT, etc.). In addition, smaller vessels (such as high-speed patrol boats) will be considered since they also carry potentially significant offensive weapons.

Although over-the-horizon targeting (OTHT) is not expected to be readily available to the enemy vessels, the Corvette 2100 will have to be able to use OTHT to obtain a clear advantage.

Land-based aircraft and/or seaborne helicopters may constitute a threat to the Corvette 2100, thus anti-aircraft and anti-missile weapons will be required on the Corvette 2100 for self-defense.

It is also expected that, in the conflicts where the Corvette 2100 will be involved, a potential threat from mines shall be present. As a result, reduced signatures and increased survivability are required.

A minor submarine threat is anticipated, and some self defense capability against the threat of diesel submarines should be considered for the Corvette 2100.

2.4 Tactical Concept

2.4.1 Anti-Surface Warfare

The ship shall use long range weapons (SSM) in association with RPVs for early detection and surveillance and for OTHT against major targets. Small and non-threatening targets shall be monitored with RPVs and ship borne radars. Neutralization, if required, may be made using conventional guns at short range. The vessel shall use high speed to reach the area of conflict in minimum time and, if required, for tactical repositioning on site. A low-speed, stealth mode, shall be used generally while in the theater of conflict.

Satellite communications, RPVs with secure link and passive (or, if available, non-detectable active) detection means shall be used to detect and monitor targets in the theater of conflict.

2.4.2 Shore Bombardment

Shore bombardment using the main gun monitored by RPV video coverage shall be used to support land base and/or landing operations while keeping the ship at a safe distance (beyond the horizon) from the shore.

2.4.3 Special Warfare Operations

The ship shall deploy and support commando troops with RHIBs. RPVs may be used to survey the area of operation and provide information about the threat. The guns may be used to neutralize small strike boats (terrorists) at short range.

2.4.4 Anti-Air Warfare

Anti-air missiles and/or CIWS shall be used against aircraft and missiles threats. Detection shall be provided by surface - air search radars. It should be noted that, since it is expected that the RPVs will provide early detection of surface ships and will allow the Corvette 2100 to strike before being threatened, the air threat would come mostly from land. However, the case of a helicopter used as an OTHT device by an enemy ship shall be considered. Chaff decoys (see below) shall be used as a last resort.

2.4.5 Electronic Warfare

The Corvette 2100 shall operate in the theater of operation in a "stealth" mode, that is, at low speed and with mostly passive systems. Radar detectors and jammers, as well as chaff decoy systems shall be used when required.

2.4.6 Anti-Submarine Warfare

Only conventional (diesel) submarines are considered here. Detection shall be provided by a hull-mounted sonar and neutralization shall be made by homing torpedoes. This task is only considered as a self defense capability.

2.4.7 EEZ Patrol

In peacetime, the Corvette 2100 may be used as an EEZ patrol vessel. The RPVs will provide continuous surveillance together with shipborne radars. RPVs may also be used to assess and monitor vessels in the EEZ without intercepting them by the ship itself. The RHIB and special warfare troops may be used to board and seize vessels when required.

2.4.8 Pollution Control

The Corvette 2100 may also be used in peacetime to enforce pollution control laws and to coordinate pollution control operations in case of environmental disaster and to carry out early containment. First intervention equipment shall be carried as part of the vessels payload for such purposes.

3.0 TECHNICAL CONSIDERATIONS

3.1 Mission-Related Considerations

3.1.1 Operating Profile

In peacetime, the Corvette 2100 will make limited use of high speed and will operate most of the time at the best economic speed. Only in case of emergency, such as an oil spill or drug interdiction seizure, may high speed transit be required.

In time of crisis, however, a high speed transit to the theater of conflict shall be used, although high speed is not intended to be used once on site in order to keep a low profile (stealth mode), except when prosecuting a target or evading an attack.

3.1.2 Payload Description

A typical payload for the Corvette 2100 may be as follows:

- 5-inch gun
- 2 x 20 to 30 mm guns
- 8 anti-surface warfare missiles (Harpoon or lighter missiles)
- Anti-air warfare missiles (SM2 or Sea Sparrow) in VLS cells or on pod mounting (RAM)
- CIWS (Phalanx) with autonomous detection/optronic director
- Triple torpedo tube (with 3 MK46 torpdoes)
- Small arms (12.7 mm machine guns and portable arms)
- 6 RPVs and support equipment. RPVs shall be of long endurance (>4 hours), low speed (<250 kts) type and shall carry video, radar and secure communication link as payload (no payload delivery).

- Multi-purpose surface/air search radar (with passive mode)
- Fire control radar
- Navigation radars (one dedicated to RPVs monitoring)
- UHF/VHF radio communications
- Satellite communications
- Satellite navigation system (GPS)
- Secure link with RPVs
- Hull mounted sonar
- ESM/ECM
- 2 chaff decoy system (Protean)
- 1 RHIB boats for 8 fully-equipped troops
- 8 troops fully-equipped for special warfare
- Pollution control equipment (containment booms).

The total payload weight is estimated at 150 LT, including electronics, armament and ammunition.

3.1.3 Environmental Considerations

The Corvette 2100 will be able to operate in open ocean at all seasons (year-round). Since most of the Corvette 2100 mission will be in littoral areas, seakeeping will not be a principal driver in the design.

3.2 Ship-Related Considerations

3.2.1 Hull

The hull shall be of a rugged and cost-effective construction. High tensile steel (50 ksi) shall be used.

3.2.2 Propulsion

The propulsion plant shall accommodate a multi-mode feature comprising of:

- High-speed "booster" power (gas turbine, for example)
- Low-speed economic drive (diesel engines, for example).

The low-speed mode shall also be used as a "stealth" mode (reduced signatures).

3.2.3 Performance

	Requirements
Maximum Speed (kts)	27
Cruise Speed (kts)	27
Low Speed (kts)	12
Range	2000 nm at Cruise Speed Plus 1000 nm at Low Speed
Endurance	20 days
Maneuverability	State-of-the-Art
Stability	U.S. Navy Criteria

The range was defined as a "composite" range to reflect the tactical concept described in Section 2.4, whereas, the Corvette 2100 will have to reach the theater of operations at high speed and operate there at low speed until replenishment is available.

3.2.4 Manning

Minimum manning shall be accomplished through automation and integration of monitoring and control systems for all ship operations.

3.2.5 Survivability and Vulnerability

Special attention shall be paid to reduce the detectability and increase the survivability of the Corvette 2100.

Such measures are aimed at making the Corvette 2100 undetected while it enters the theater of operation and also at reducing the risk of a missile hit and of damage from mines. In addition, the ship's survivability to combat damage shall be improved using such techniques as damage containment, quick automated power distribution reconfiguration, etc. Steps should be taken to maximize the ability of the Corvette 2100 to carry out its combat tasks after being hit by a weapon (missile, mine, torpedo, etc.).

3.3 Other Considerations

3.3.1 Special Capabilities

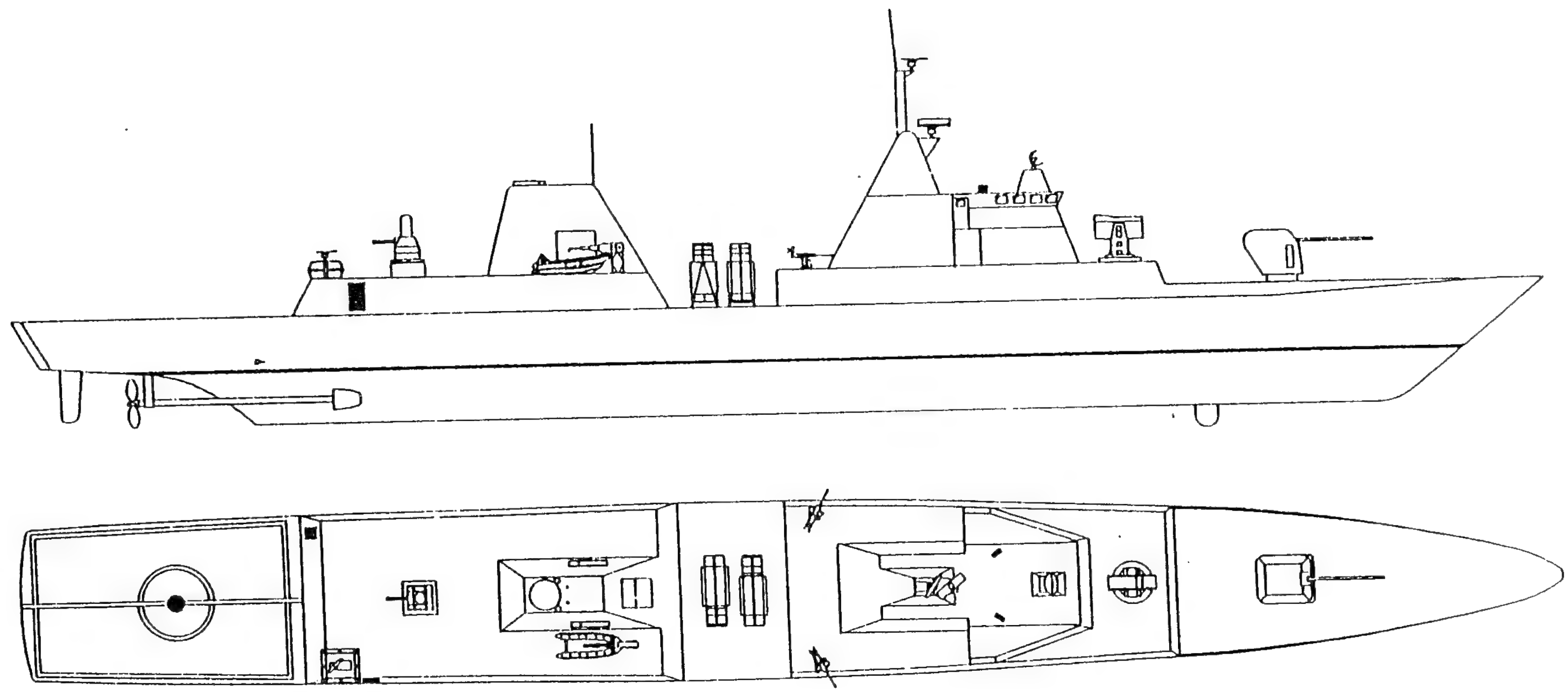
The ship combat system shall be of a modular type so as to allow quick reconfiguration, modernization throughout the lifetime of the vessel. Standardization of the auxiliary modules, power modules and control units shall be made to allow easy reconfiguration after damage or during overhaul of the vessel.

3.3.2 Readiness and Availability

A high degree of readiness and availability shall be achieved for the Corvette 2100. Such capability is expected to be possible as a result of modularity and reconfigurability as well as systematic standardization.

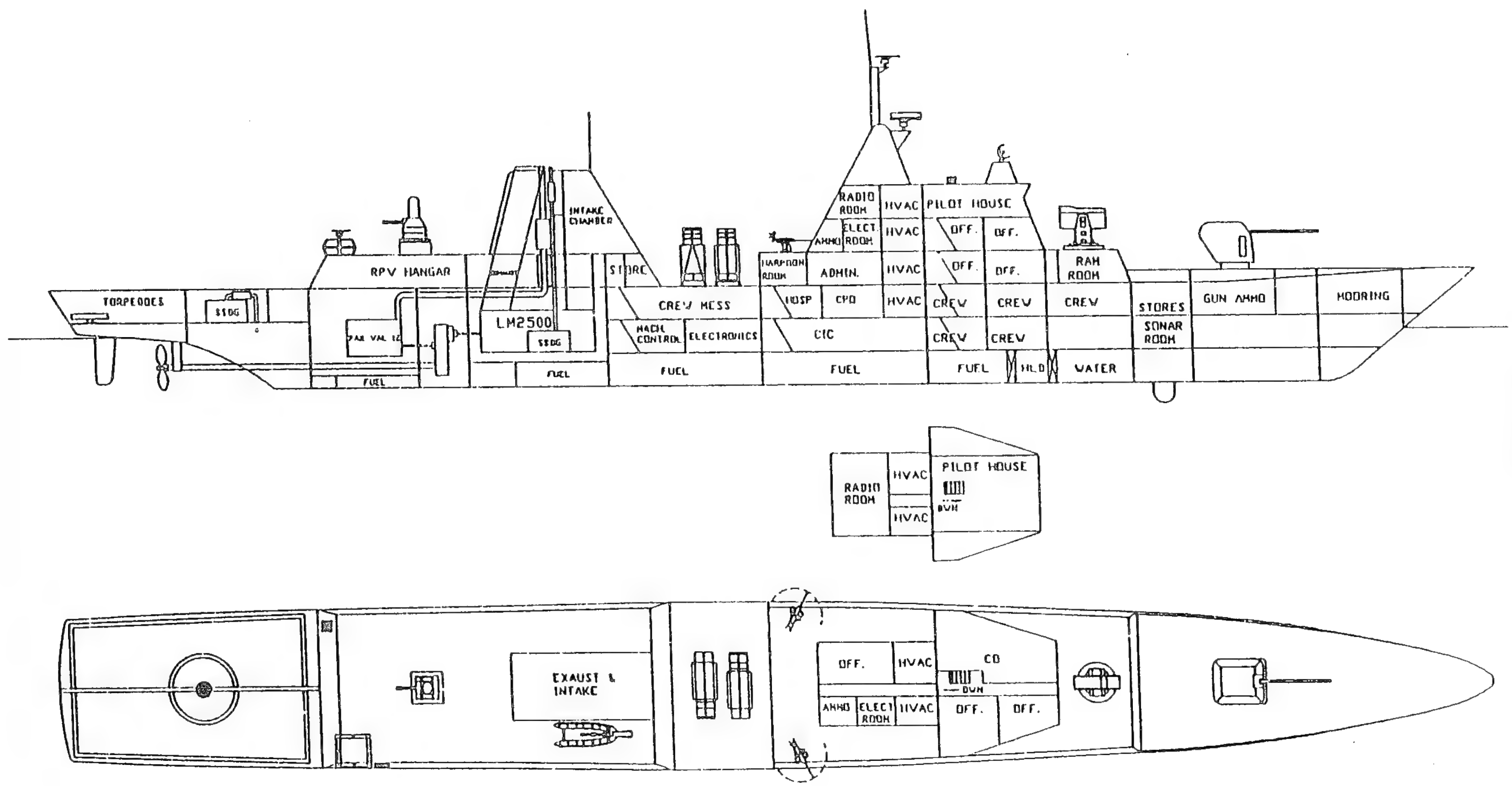
3.3.3 Overhaul, Maintenance and Logistic Support

Overhaul and maintenance are to be facilitated by systematic standardization and modularization. Subsystem maintenance may be achieved by simply replacing the subsystem by a module from a joint pool for all vessels and repairing the failed module on shore.



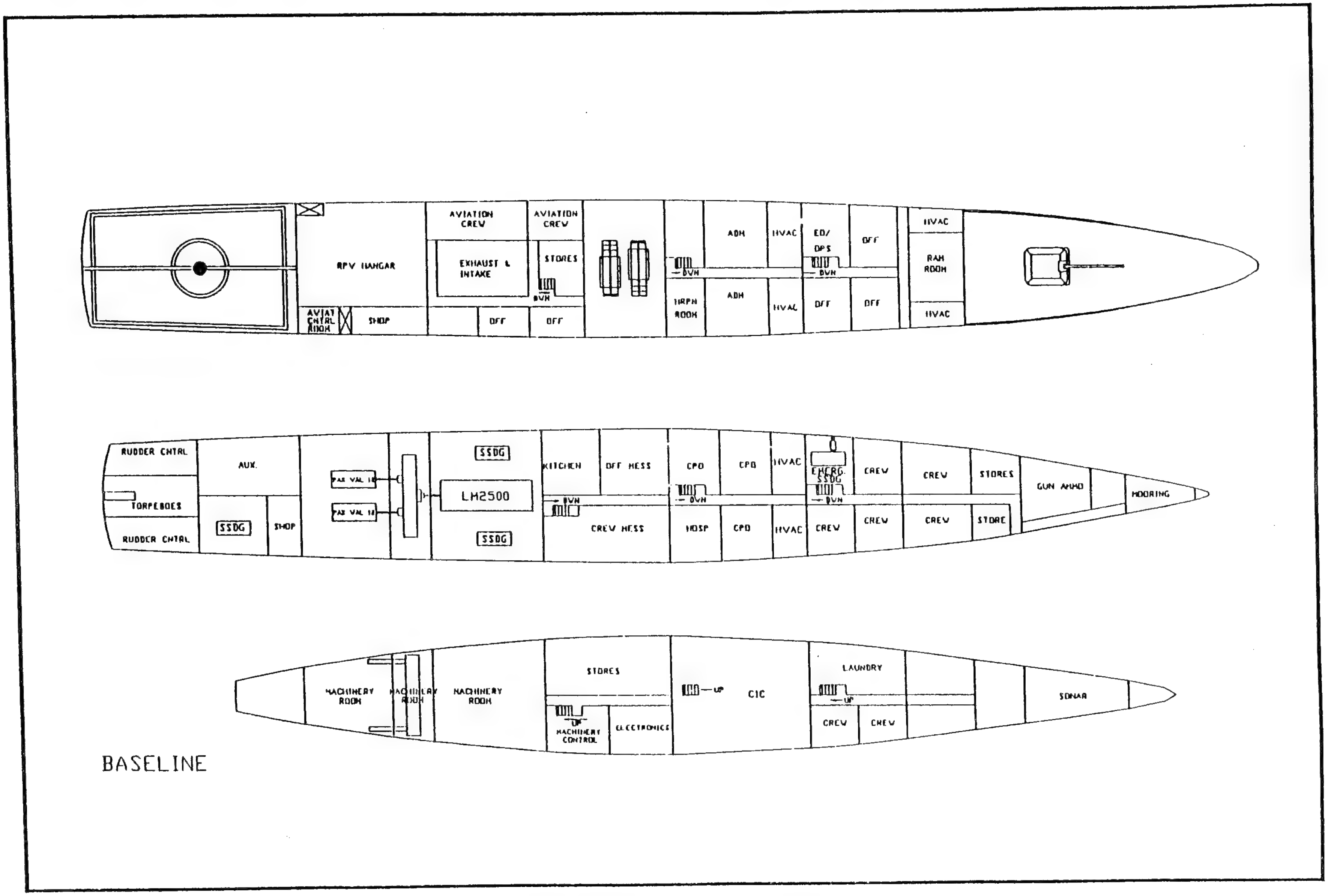
Corvette Baseline - Outboard Profile and Plan View

Figure C-1A



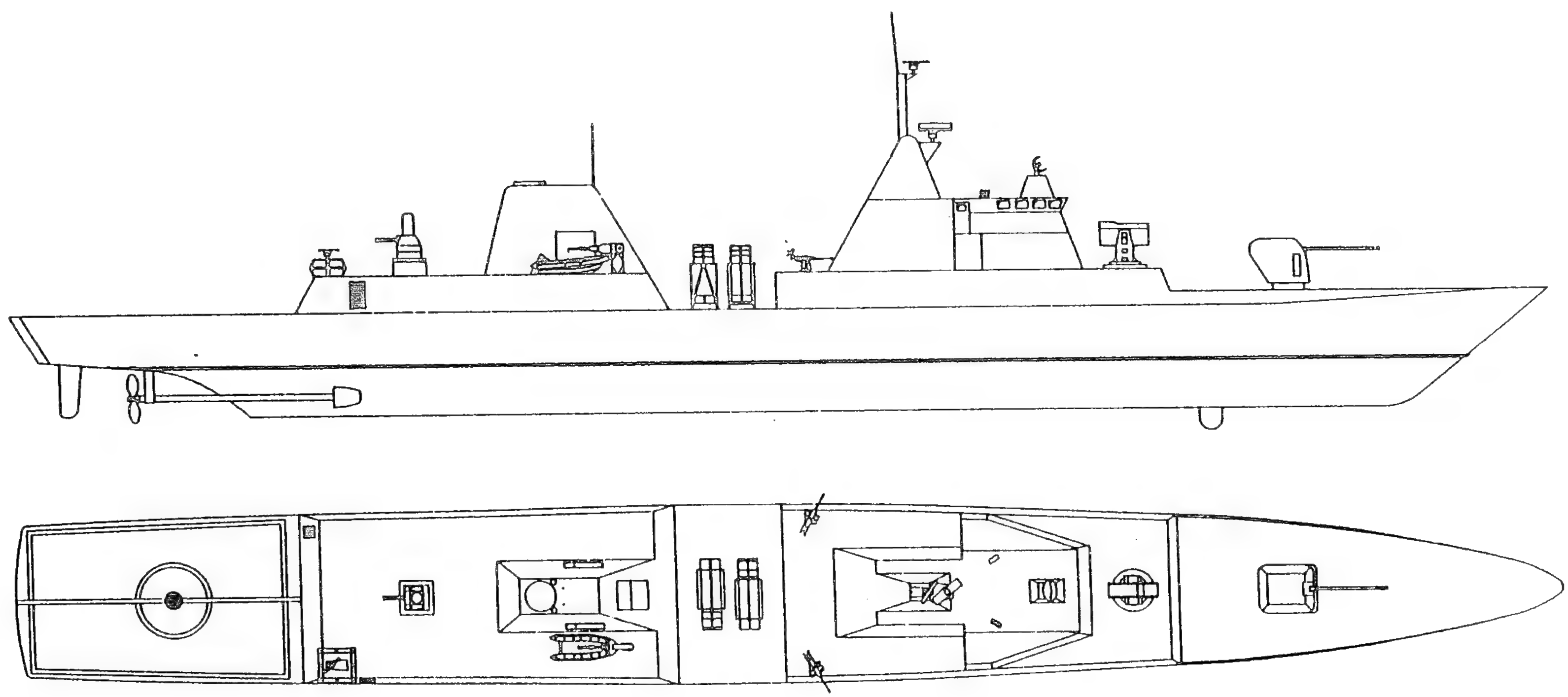
Corvette Baseline - Inboard Profile and Superstructure Arrangements

Figure C-1B



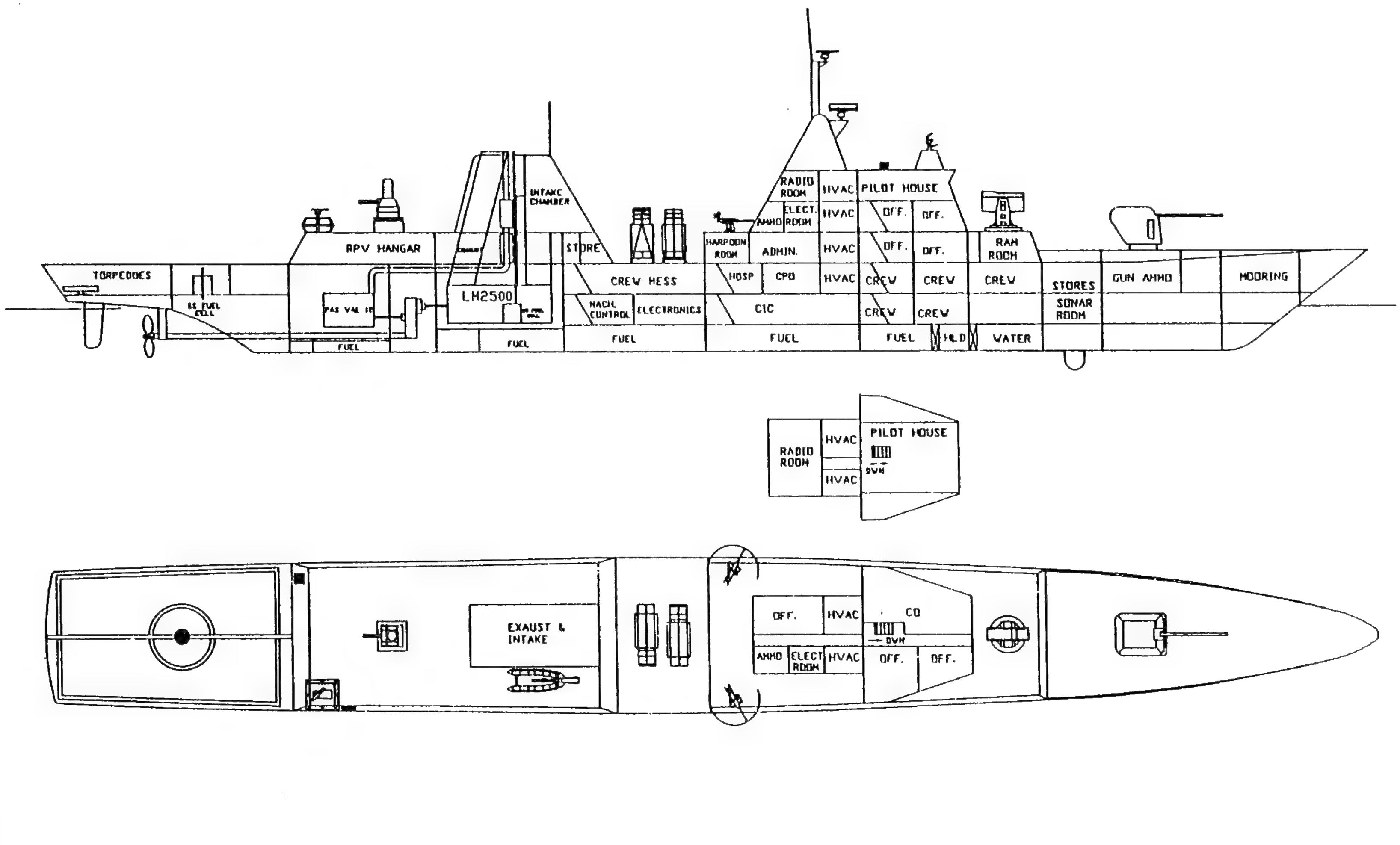
Corvette Baseline - Internal Arrangement

Figure C-1C



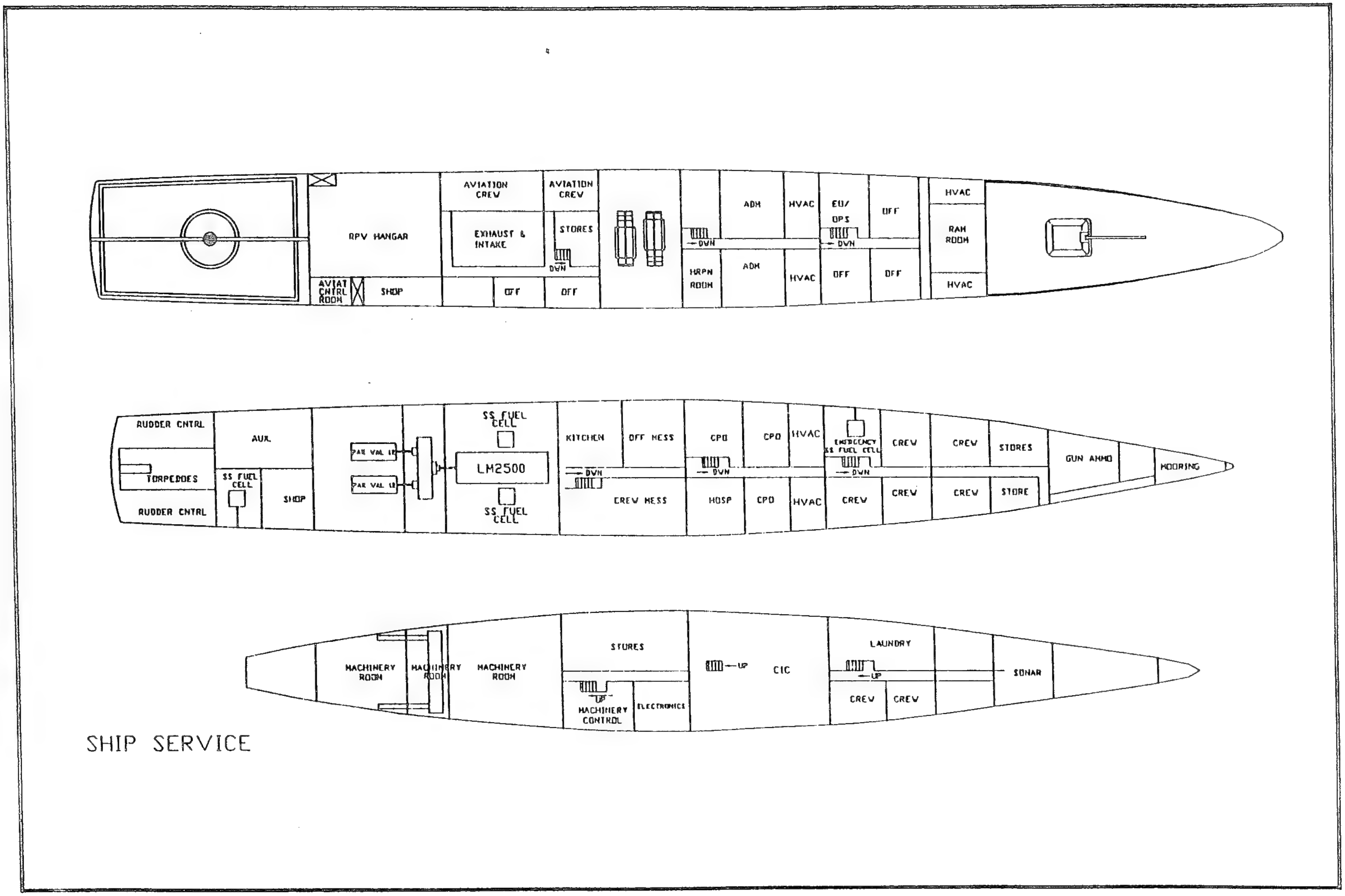
PEM Ship Service Power - Outboard Profile and Plan View

Figure C-2A



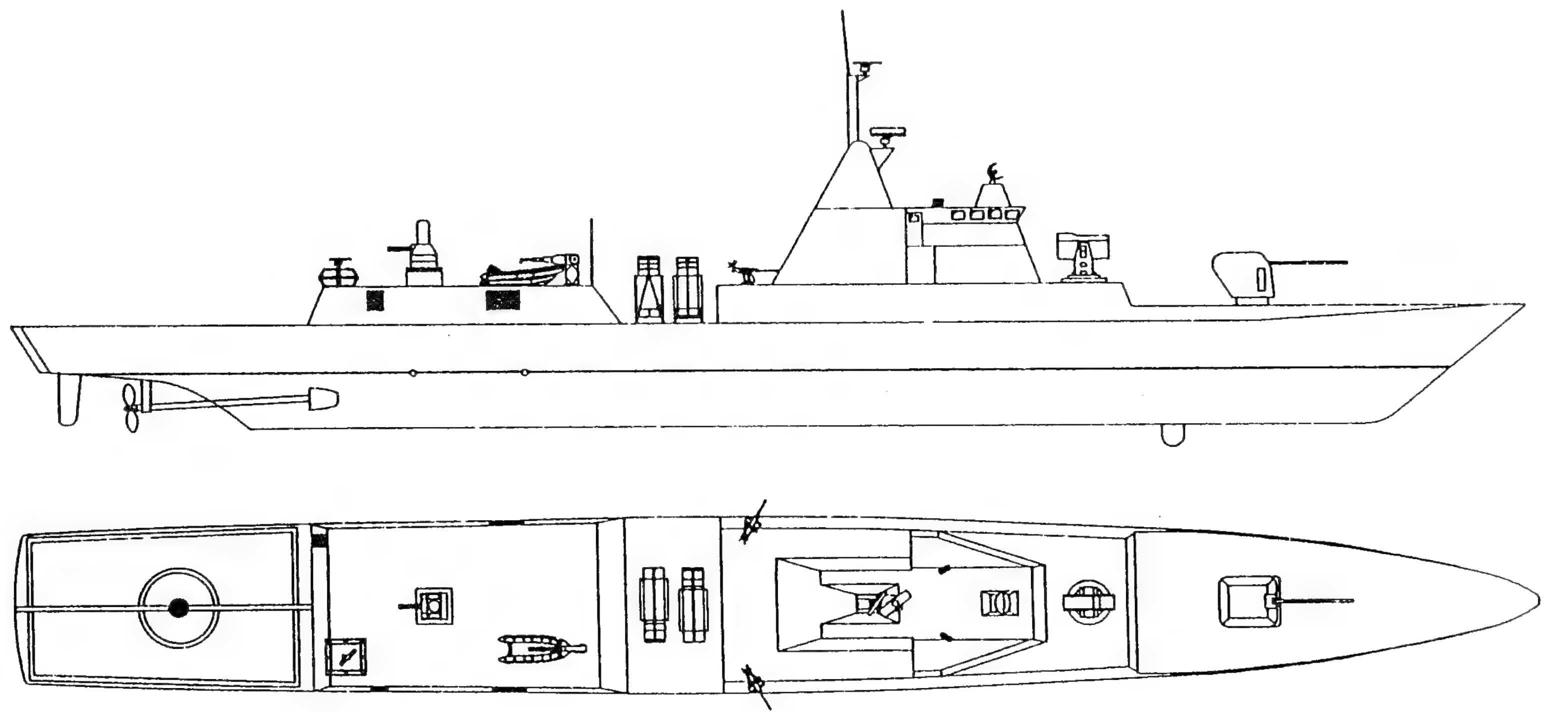
PEM Ship Service Power - Inboard Profile and Superstructure Arrangements

Figure C-2B



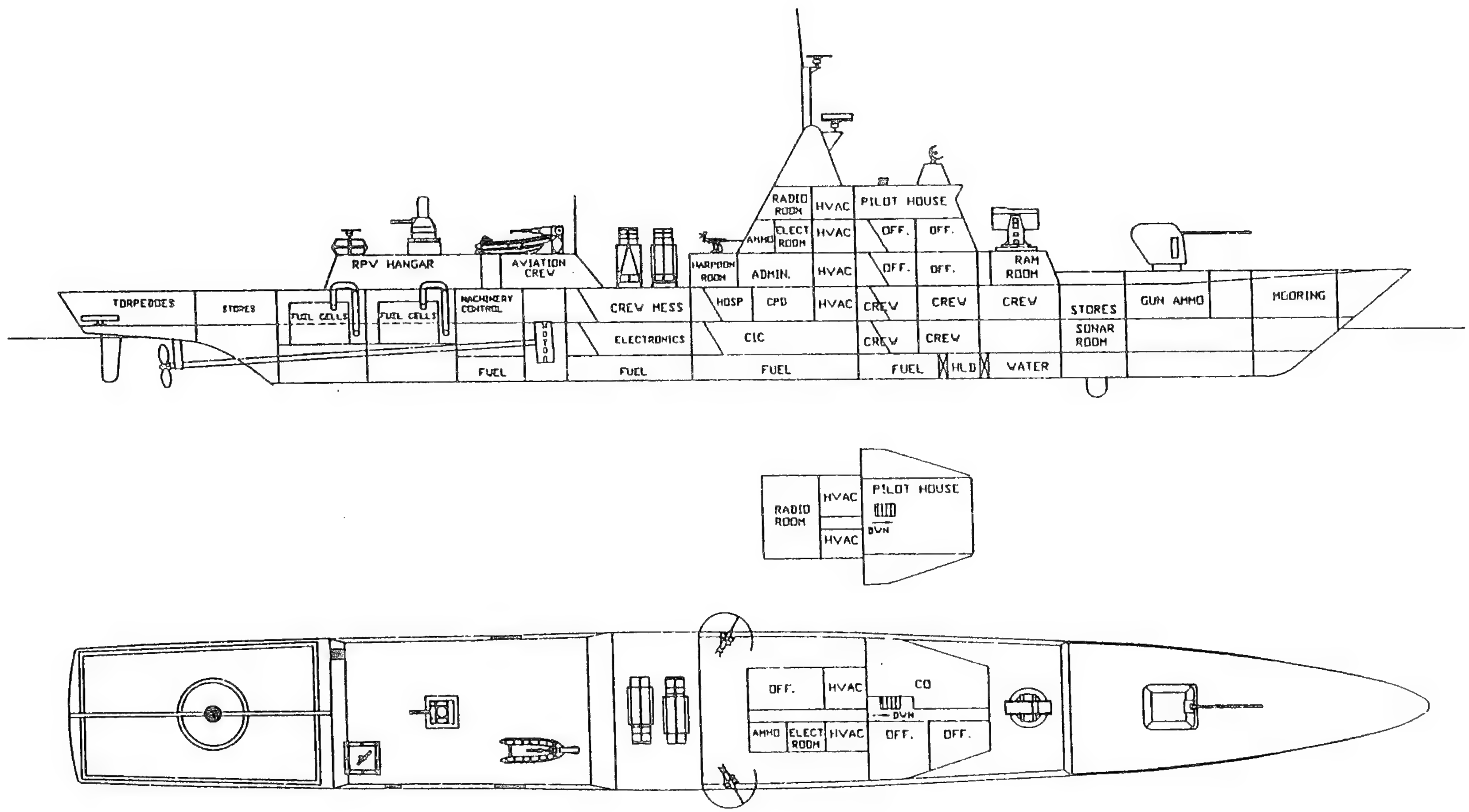
PEM Ship Service Power - Internal Arrangements

Figure C-2C



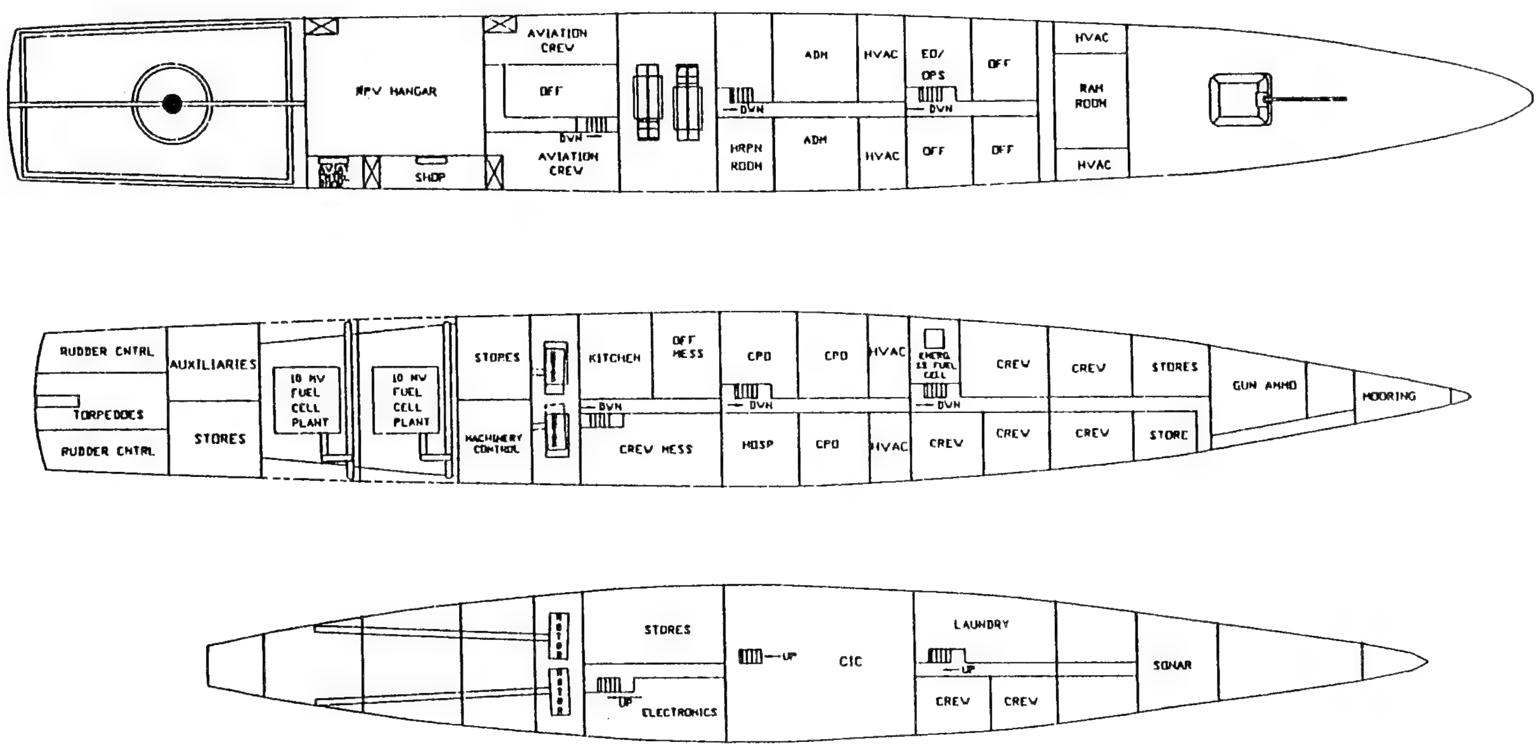
PEM Propulsion - Outboard Profile and Plan View

Figure C-3A



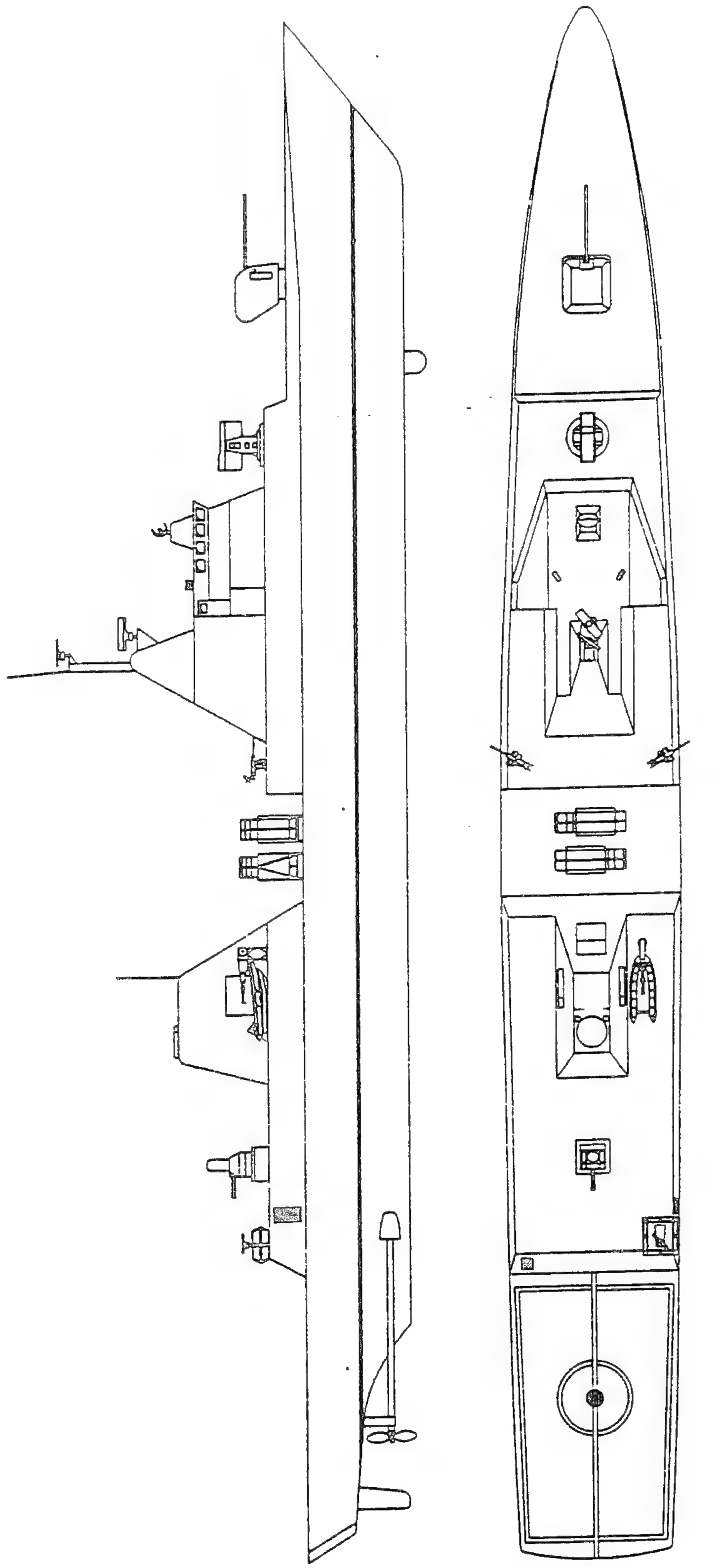
PEM Propulsion - Inboard Profile and Superstructure Arrangements

Figure C-3B



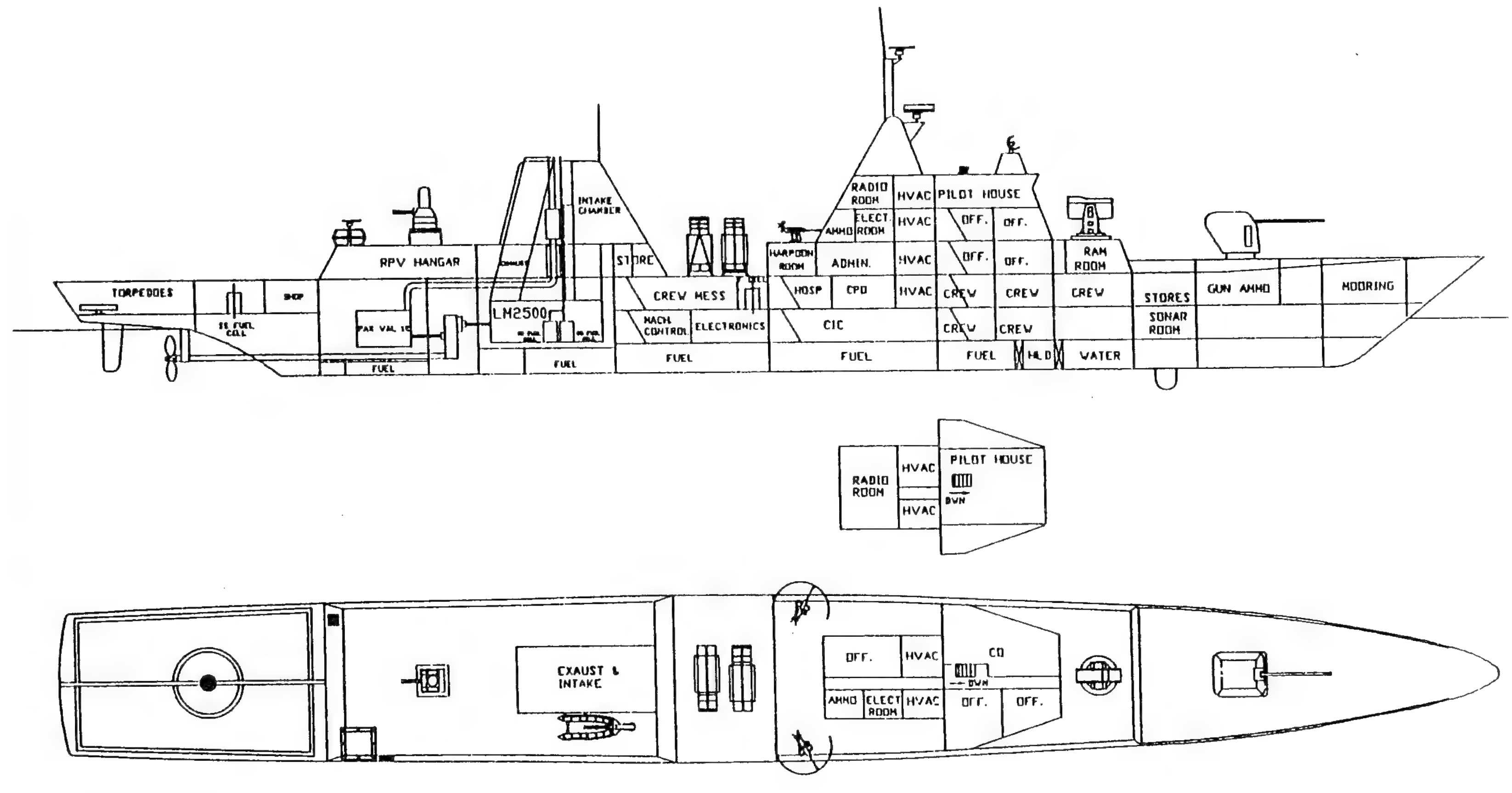
PEM Propulsion - Internal Arrangements

Figure C-3C



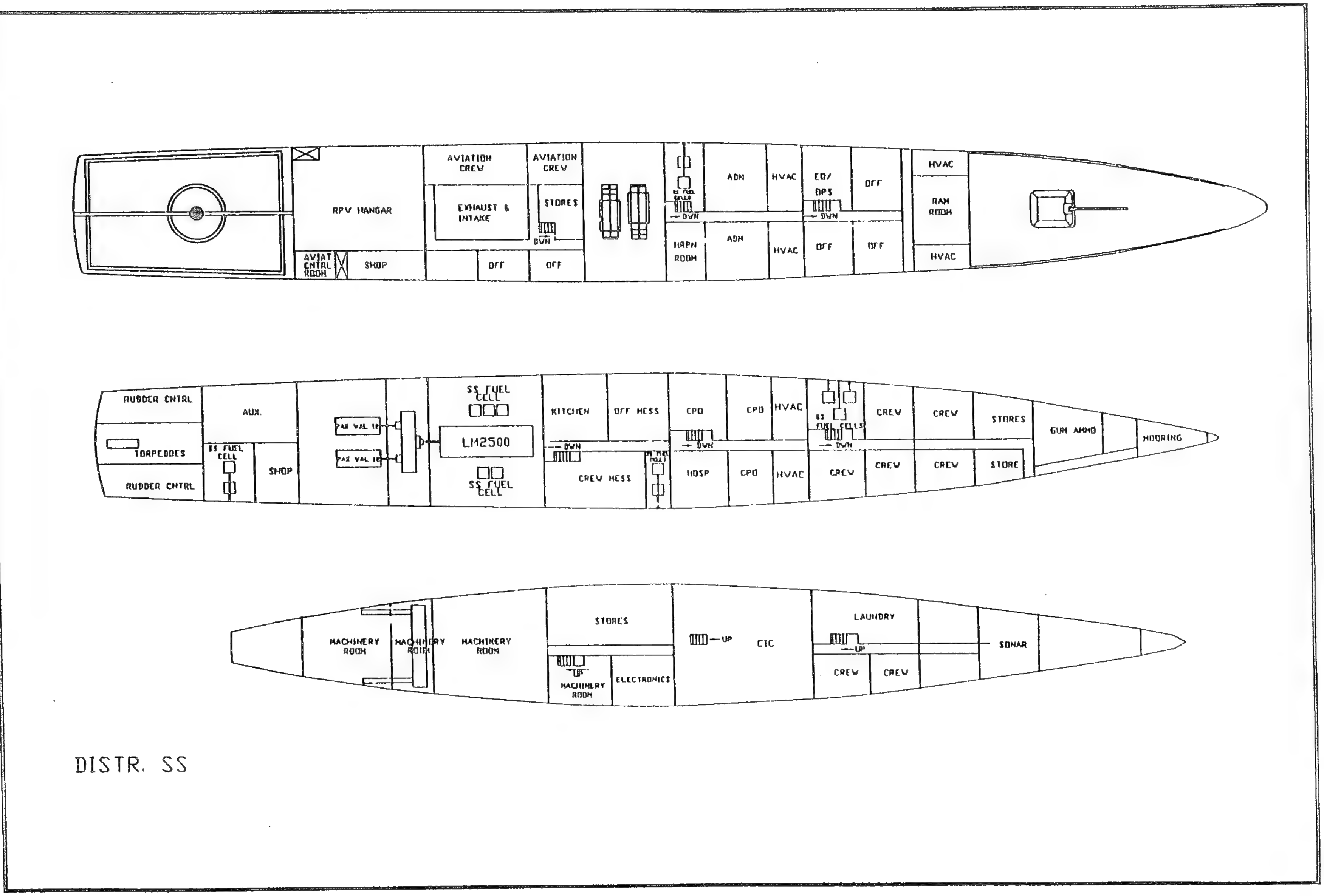
PEM Distributed Ship Service Power - Outboard Profile and Plan View

Figure C-4A



PEM Distributed Ship Service Power - Inboard Profile and Superstructure Arrangements

Figure C-4B



PEM Distributed Ship Service Power - Internal Arrangement

Figure C-4C

APPENDIX D

DESTROYER, SHIP IMPACT, ADDITIONAL INFORMATION

DESIGN METHODOLOGY FOR DESTROYER

$$CircleM = \frac{lbp}{(35 \times Disp)^{(\frac{1}{3})}}$$

$$C_x = 0.743539 + 0.000013 \times Disp - 4.15999E\text{-}10 \times Disp^2 + 4.917054E\text{-}15 \times Disp^3$$

$$C_p = 4.067678 - 9.515995 \times (\frac{V}{lbp^{.5}}) + 9.413578 \times (\frac{V}{lbp^{.5}})^2 - 4.004274 \times (\frac{V}{lbp^{.5}})^3 + 0.623543 \times (\frac{V}{lbp^{.5}})^4$$

where:	lbp	= length between perpendiculars
	Disp	= Full Load Displacement
	Cx	= Maximum Section Coefficient
	Cp	= Prismatic Coefficient
	V	= Maximum Speed

The baseline Destroyer was iterated until a balance was achieved between Circle M, Displacement, Cx, and Cp. Subsequently, this Circle M was held constant for all of the variants. For the variants, the designs were iterated considering the above equations until a consistent design was achieved for all of the variables while maintaining the constant Circle M value.

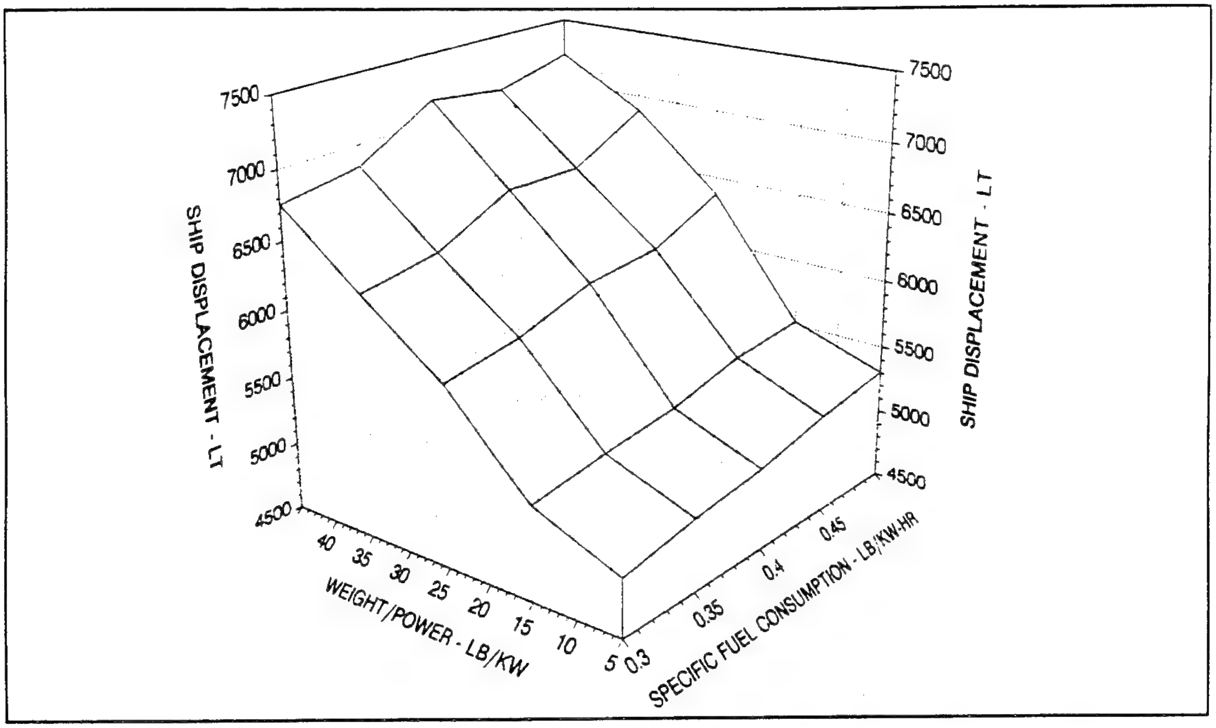
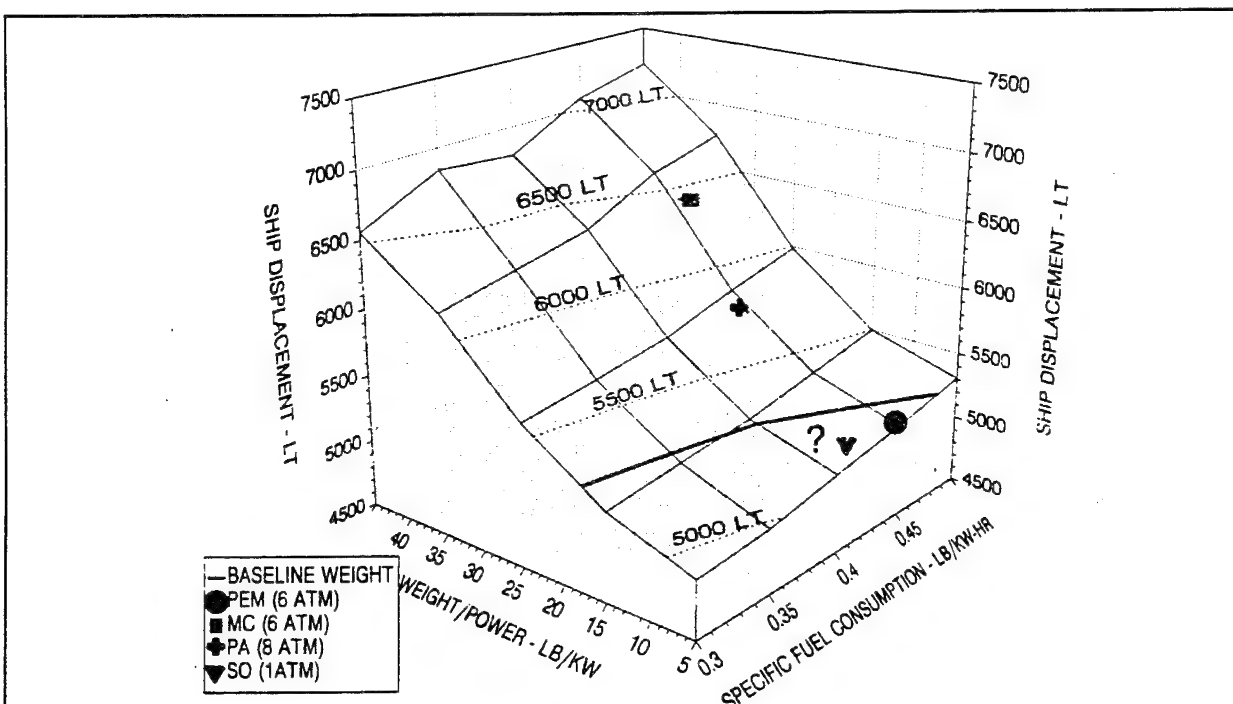


Figure D-1. Ship Displacement Versus Power Density and SFC Plant Density = 20 lb/ft^3



NOTE: THE ? SYMBOL, BESIDE THE SOFC DATA POINT, MEANS VERIFICATION IS NEEDED.

Figure D-2. Ship Displacement Versus Power Density and SFC Plant Density = 30 lb/ft^3

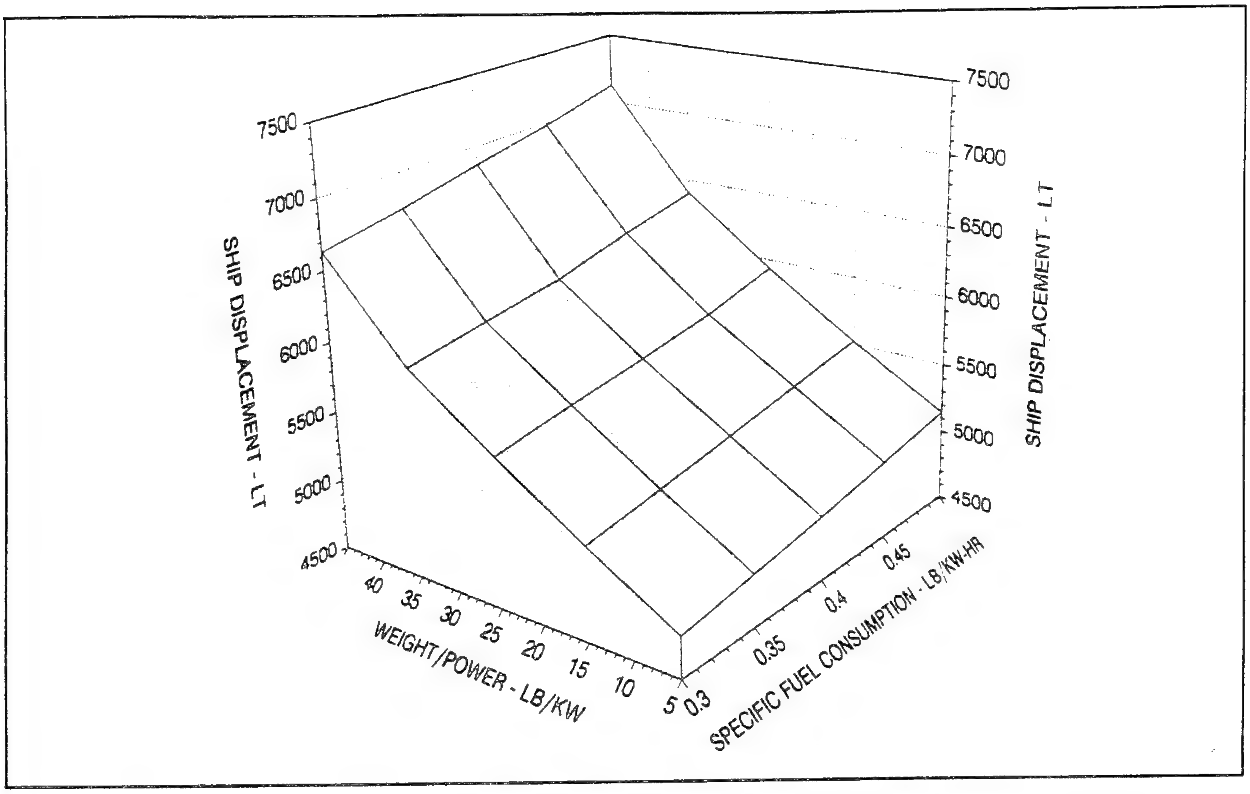


Figure D-3. Ship Displacement Versus Power Density and SFC Plant Density = 40 lb/ft^3

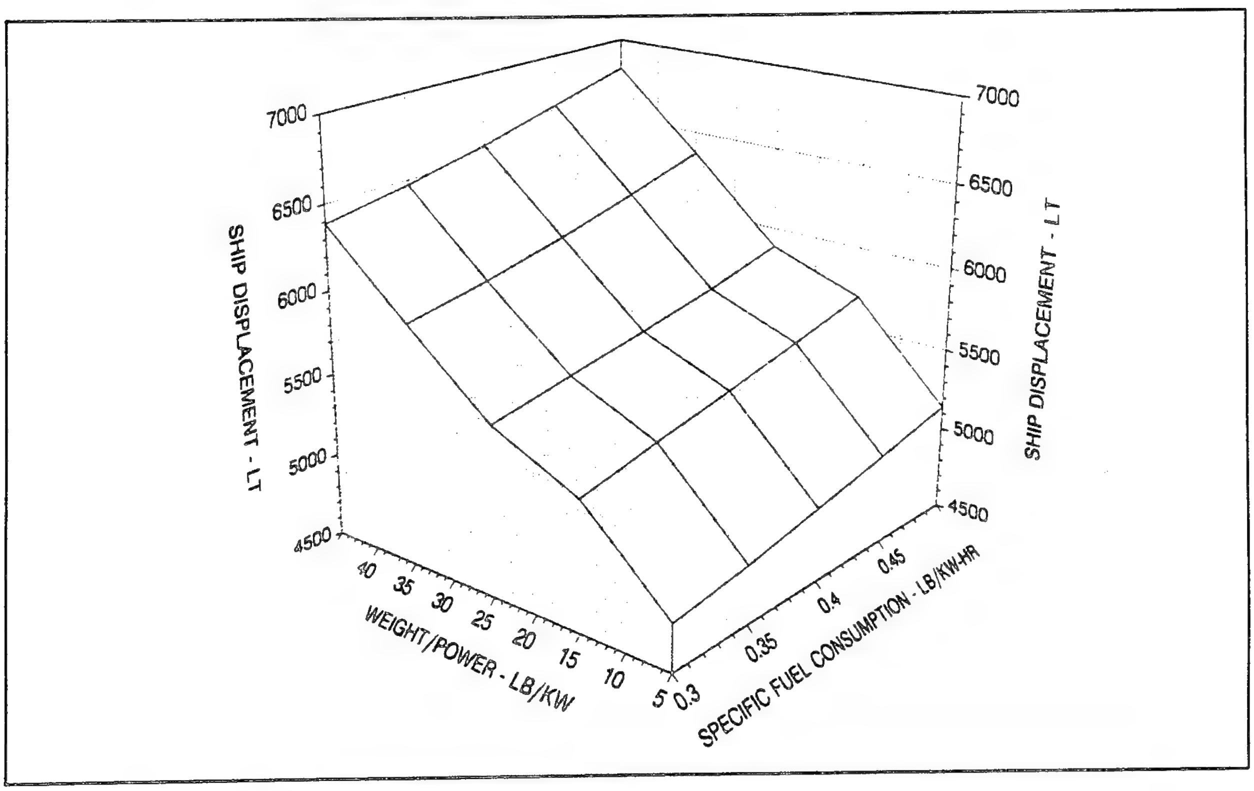


Figure D-4. Ship Displacement Versus Power Density and SFC Plant Density = 50 lb/ft^3

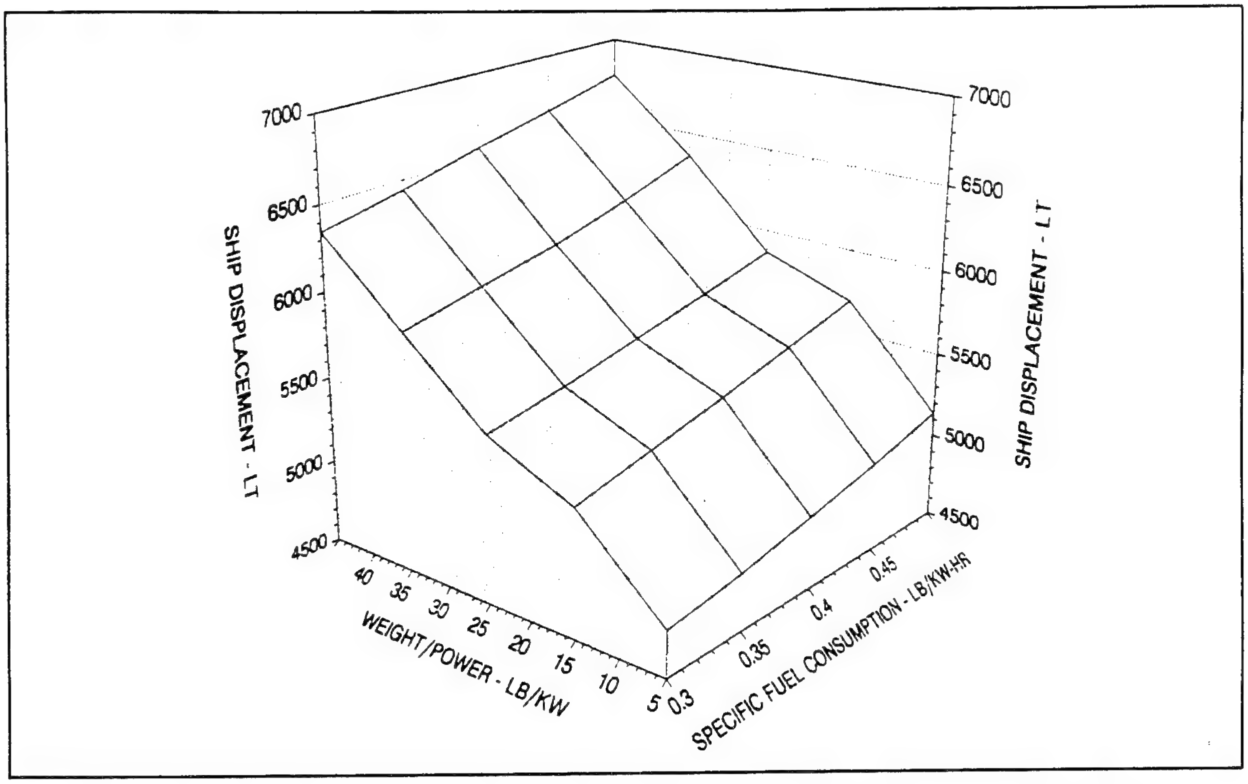


Figure D-5. Ship Displacement Versus Power Density and SFC Plant Density = 60 lb/ft^3

SWBS WEIGHTS FOR ASSET, DESTROYER BASELINE

BASELINE DESTROYER - 3-DIGIT WEIGHT REPORT

ASSET/MONOSC VERSION 3.3A - WEIGHT MODULE - 9-MAR-94 20.04.25.

PRINTED REPORT NO. 1 - SUMMARY

SWBS	GROUP	WEIGHT LTON	WEIGHT PER CENT	LCG FT	VCG FT	RESULTANT WT-LTON	ADJ VCG-FT
100	HULL STRUCTURE	1707.6	32.4	210.95	25.35	50.0	.59
200	PROP PLANT	445.5	8.5	274.07	13.22		
300	ELECT PLANT	156.7	3.0	234.80	22.43		
400	COMM + SURVEIL	256.6	4.9	161.50	27.77	96.7	.88
500	AUX SYSTEMS	625.6	11.9	233.75	23.41		
600	OUTFIT + FURN	476.1	9.0	212.50	23.71	1.3	.01
700	ARMAMENT	190.4	3.6	191.25	28.43	178.8	.97
M11	D+B WT MARGIN	385.8	7.3	218.83	23.62		
	D+B KG MARGIN			+	2.35		
	LIGHTSHIP	4244.3	80.5	218.83	25.99	326.8	2.47
F00	FULL LOADS	1024.9	19.5	199.36	12.24	263.7	1.30
F10	CREW + EFFECTS	23.4		199.75	25.40		
F20	MISS REL EXPEN	211.9		187.00	30.00		
F30	SHIPS STORES	36.3		229.50	19.32		
F40	FUELS + LUBRIC	719.9		201.72	6.58		
F50	FRESH WATER	33.4			4.79		
F60	CARGO						
M24	FUTURE GROWTH						
	FULL LOAD WT	5269.2	100.0	215.04	23.32	590.5	3.78

PRINTED REPORT NO. 2 - HULL STRUCTURES WEIGHT

SWBS	COMPONENT	WT-LTON	VCG-FT
100	HULL STRUCTURES	1707.5	25.35
110	SHELL + SUPPORTS	459.7	15.82
111	PLATING	287.8	20.25
113	INNER BOTTOM	47.0	4.00
114	SHELL APPENDAGES	13.6	5.42
115	STANCHIONS	5.3	16.39
116	LONGIT FRAMING	47.5	1.00
117	TRANSV FRAMING	58.2	18.04
120	HULL STRUCTURAL BULKHDS	123.9	20.60
121	LONGIT STRUCTURAL BULKHDS		
122	TRANSV STRUCTURAL BULKHDS	105.9	20.60
123	TRUNKS + ENCLOSURES	18.0	20.60
124	BULKHEADS, TORPEDO PROTECT SYS		
130	HULL DECKS	184.6	34.47
131	MAIN DECK	184.6	34.47
132	2ND DECK		
133	3RD DECK		
134	4TH DECK		
135	5TH DECK+DECKS BELOW		
136	01 HULL DECK		
137	02 HULL DECK		
138	03 HULL DECK		
139	04 HULL DECK		
140	HULL PLATFORMS/FLATS	175.6	20.32
141	1ST PLATFORM	111.5	24.35
142	2ND PLATFORM	64.0	13.34

	143 3RD PLATFORM		
	144 4TH PLATFORM		
	145 5TH PLAT+PLATS BELOW		
	149 FLATS		
	150 DECK HOUSE STRUCTURE	333.8	42.52
	160 SPECIAL STRUCTURES	174.5	27.07
	161 CASTINGS+FORGINGS+EQUIV WELDMT	41.2	11.73
	162 STACKS AND MACKS	3.7	56.95
	163 SEA CHESTS	4.5	3.69
*	164 BALLISTIC PLATING	50.0	62.80
	165 SONAR DOMES	40.0	-2.00
	166 SPONSONS		
	167 HULL STRUCTURAL CLOSURES	27.3	24.28
	168 DKHS STRUCTURAL CLOSURES	1.2	46.00
	169 SPECIAL PURPOSE CLOSURES+STRUCT	6.3	36.54
	170 MASTS+KINGPOSTS+SERV PLATFORM	15.5	88.05
	171 MASTS,TOWERS,TETRAPODS	15.5	88.05
	172 KINGPOSTS AND SUPPORT FRAMES		
	179 SERVICE PLATFORMS		
	180 FOUNDATIONS	223.0	14.22
	181 HULL STRUCTURE FOUNDATIONS		
	182 PROPULSION PLANT FOUNDATIONS	102.9	6.94
	183 ELECTRIC PLANT FOUNDATIONS	16.3	16.69
	184 COMMAND+SURVEILLANCE FDNS	17.3	31.26
	185 AUXILIARY SYSTEMS FOUNDATIONS	62.6	17.46
	186 OUTFIT+FURNISHINGS FOUNDATIONS	9.5	23.19
	187 ARMAMENT FOUNDATIONS	14.3	23.05
	190 SPECIAL PURPOSE SYSTEMS	16.8	4.00
	191 BALLAST+BOUYANCY UNITS		
	197 WELDING AND RIVETS		
	198 FREE FLOODING LIQUIDS	16.8	4.00

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 3 - PROPULSION PLANT WEIGHT

	SWBS	COMPONENT	WT-LTON	VCG-FT
	====	=========	=============	============
	200	PROPULSION PLANT	445.5	13.21
	210	ENERGY GEN SYS (NUCLEAR)		
	220	ENERGY GENERATING SYSTEM (NONNUC)		
	221	PROPULSION BOILERS		
	222	GAS GENERATORS		
	223	MAIN PROPULSION BATTERIES		
	224	MAIN PROPULSION FUEL CELLS		
	230	PROPULSION UNITS	198.0	11.46
	231	STEAM TURBINES		
	232	STEAM ENGINES		
	233	DIESEL ENGINES		
	234	GAS TURBINES	98.2	13.71
*	235	ELECTRIC PROPULSION	99.7	9.26
	236	SELF-CONTAINED PROPULSION SYS		
	237	AUXILIARY PROPULSION DEVICES		
	240	TRANSMISSION+PROPULSOR SYSTEMS	118.2	4.25
	241	REDUCTION GEARS		
	242	CLUTCHES + COUPLINGS		
*	243	SHAFTING	78.0	4.81
*	244	SHAFT BEARINGS	16.8	5.40
	245	PROPULSORS	23.3	1.54
	246	PROPULSOR SHROUDS AND DUCTS		
	247	WATER JET PROPULSORS		
	250	SUPPORT SYSTEMS	86.8	30.50
	251	COMBUSTION AIR SYSTEM	21.3	30.54
	252	PROPULSION CONTROL SYSTEM	13.6	21.32

	253	MAIN STEAM PIPING SYSTEM		
	254	CONDENSERS AND AIR EJECTORS		
	255	FEED AND CONDENSATE SYSTEM		
*	256	CIRC + COOL SEA WATER SYSTEM	18.8	14.31
	258	H.P. STEAM DRAIN SYSTEM		
	259	UPTAKES (INNER CASING)	32.9	43.55
	260	PROPUL SUP SYS- FUEL, LUBE OIL	22.2	11.98
	261	FUEL SERVICE SYSTEM	4.7	7.71
	262	MAIN PROPULSION LUBE OIL SYSTEM	12.5	12.00
	264	LUBE OIL HANDLING	5.0	16.00
	290	SPECIAL PURPOSE SYSTEMS	20.3	9.92
	298	OPERATING FLUIDS	15.1	8.00
	299	REPAIR PARTS + TOOLS	5.3	15.42

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 4 - ELECTRIC PLANT WEIGHT

	SWBS	COMPONENT	WT-LTON	VCG-FT
	300	ELECTRIC PLANT, GENERAL	156.6	22.43
	310	ELECTRIC POWER GENERATION	54.0	17.62
	311	SHIP SERVICE POWER GENERATION	31.1	10.67
	312	EMERGENCY GENERATORS		
	313	BATTERIES+SERVICE FACILITIES		
	314	POWER CONVERSION EQUIPMENT	22.8	27.07
	320	POWER DISTRIBUTION SYS	73.8	23.98
*	321	SHIP SERVICE POWER CABLE	39.6	27.00
	322	EMERGENCY POWER CABLE SYS		
	323	CASUALTY POWER CABLE SYS		
*	324	SWITCHGEAR+PANELS	34.2	20.52
	330	LIGHTING SYSTEM	15.1	29.88
*	331	LIGHTING DISTRIBUTION	6.8	29.52
*	332	LIGHTING FIXTURES	8.4	30.17
	340	POWER GENERATION SUPPORT SYS	11.4	25.94
	341	SSTG LUBE OIL		
	342	DIESEL SUPPORT SYS		
	343	TURBINE SUPPORT SYS	11.4	25.94
	390	SPECIAL PURPOSE SYS	2.2	18.04
	398	ELECTRIC PLANT OP FLUIDS	.6	10.67
	399	REPAIR PARTS+SPECIAL TOOLS	1.6	21.00

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 5 - COMMAND+SURVEILLANCE WEIGHT

	SWBS	COMPONENT	WT-LTON	VCG-FT
	400	COMMAND+SURVEILLANCE	256.6	27.76
	410	COMMAND+CONTROL SYS	18.8	28.39
*	411	DATA DISPLAY GROUP	17.3	28.43
*	412	DATA PROCESSING GROUP	1.6	27.88
	413	DIGITAL DATA SWITCHBOARDS		
	414	INTERFACE EQUIPMENT		
	415	DIGITAL DATA COMMUNICATIONS		
	417	COMMAND+CONTROL ANALOG SWBD		
	420	NAVIGATION SYS	8.8	54.70
	430	INTERIOR COMMUNICATIONS	27.8	28.10
*	440	EXTERIOR COMMUNICATIONS	22.6	49.89
	441	RADIO SYSTEMS		
	442	UNDERWATER SYSTEMS		
	443	VISUAL + AUDIBLE SYSTEMS		
	444	TELEMETRY SYSTEMS		
	445	TTY + FACSIMILE SYSTEMS		

	SWBS	COMPONENT	WT-LTON	VCG-FT
	446	SECURITY EQUIPMENT SYSTEMS		
	450	SURF SURV SYS (RADAR)	19.0	75.31
*	451	SURFACE SEARCH RADAR	1.9	53.50
	452	AIR SEARCH RADAR (2D)		
	453	AIR SEARCH RADAR (3D)		
	454	AIRCRAFT CONTROL APPROACH RADAR		
*	455	IDENTIFICATION SYSTEMS (IFF)	2.1	77.09
*	456	MULTIPLE MODE RADAR	15.0	77.80
	459	SPACE VEHICLE ELECTRONIC TRACKG		
	460	UNDERWATER SURVEILLANCE SYSTEMS	47.5	7.91
*	461	ACTIVE SONAR	47.0	7.71
	462	PASSIVE SONAR		
	463	MULTIPLE MODE SONAR		
	464	CLASSIFICATION SONAR		
*	465	BATHYTHERMOGRAPH	.5	29.72
	466	LAMPS ELECTRONICS		
	470	COUNTERMEASURES	38.9	33.77
*	471	ACTIVE + ACTIVE/PASSIVE ECM	6.5	63.47
	472	PASSIVE ECM		
*	473	TORPEDO DECOYS	9.1	29.52
*	474	DECOYS (OTHER)	2.6	55.21
	475	DEGAUSSING	20.6	23.60
	476	MINE COUNTERMEASURES		
	480	FIRE CONTROL SYS	17.5	41.47
*	481	GUN FIRE CONTROL SYSTEMS	1.8	31.68
*	482	MISSILE FIRE CONTROL SYSTEMS	15.1	43.11
*	483	UNDERWATER FIRE CONTROL SYSTEMS	.5	27.88
	484	INTEGRATED FIRE CONTROL SYSTEMS		
	489	WEAPON SYSTEM SWITCHBOARDS		
	490	SPECIAL PURPOSE SYS	55.7	6.35
	491	ELCTRNC TEST,CHKOUT,MONITR EQPT	3.9	39.89
	492	FLIGHT CNTRL+INSTR LANDING SYS		
	493	NON-COMBAT DATA PROCESSING SYS	3.5	25.23
	494	METEOROLOGICAL SYSTEMS		
	495	SPEC PURPOSE INTELLIGENCE SYS		
	498	C+S OPERATING FLUIDS	45.0	.26
	499	REPAIR PARTS+SPECIAL TOOLS	3.2	29.84

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 6 - AUXILIARY SYSTEMS WEIGHT

SWBS	COMPONENT	WT-LTON	VCG-FT
500	AUXILIARY SYSTEMS, GENERAL	625.6	23.40
510	CLIMATE CONTROL	175.1	26.62
511	COMPARTMENT HEATING SYSTEM	6.8	29.86
512	VENTILATION SYSTEM	66.3	33.50
513	MACHINERY SPACE VENT SYSTEM	13.1	36.15
514	AIR CONDITIONING SYSTEM	86.0	19.93
516	REFRIGERATION SYSTEM	2.5	17.29
517	AUX BOILERS+OTHER HEAT SOURCES	.4	20.37
520	SEA WATER SYSTEMS	71.8	21.40
521	FIREMAIN+SEA WATER FLUSHING SYS	40.0	20.73
522	SPRINKLING SYSTEM		25.22
523	WASHDOWN SYSTEM	3.6	39.96
524	AUXILIARY SEAWATER SYSTEM		
526	SCUPPERS+DECK DRAINS	1.2	36.82
527	FIREMAIN ACTUATED SERV, OTHER		
528	PLUMBING DRAINAGE	19.0	22.69
529	DRAINAGE+BALLASTING SYSTEM	8.0	10.96
530	FRESH WATER SYSTEMS	45.7	21.17
531	DISTILLING PLANT	7.0	17.59
532	COOLING WATER	8.8	33.89

	533	POTABLE WATER	14.8	22.76
	534	AUX STEAM + DRAINS IN MACH BOX	15.1	13.81
	535	AUX STEAM + DRAINS OUT MACH BOX		
	536	AUXILIARY FRESH WATER COOLING		
	540	FUELS/LUBRICANTS,HANDLING+STORAGE	45.6	15.60
	541	SHIP FUEL+COMPENSATING SYSTEM	37.2	14.86
*	542	AVIATION+GENERAL PURPOSE FUELS	7.0	21.70
	543	AVIATION+GENERAL PURPOSE LUBO		
	544	LIQUID CARGO		
	545	TANK HEATING	1.3	3.99
	549	SPEC FUEL+LUBRICANTS HANDL+STOW		
	550	AIR,GAS+MISC FLUID SYSTEM	65.9	21.57
	551	COMPRESSED AIR SYSTEMS	30.8	19.21
	552	COMPRESSED GASES		
	553	O2 N2 SYSTEM		
	554	LP BLOW		
	555	FIRE EXTINGUISHING SYSTEMS	35.0	23.65
	556	HYDRAULIC FLUID SYSTEM		
	557	LIQUID GASES, CARGO		
	558	SPECIAL PIPING SYSTEMS		
	560	SHIP CNTL SYS	38.2	10.26
	561	STEERING+DIVING CNTL SYS	11.5	17.86
	562	RUDDER	26.7	7.01
	565	TRIM+HEEL SYSTEMS		
	568	MANEUVERING SYSTEMS		
	570	UNDERWAY REPLENISHMENT SYSTEMS	35.7	29.67
	571	REPLENISHMENT-AT-SEA SYSTEMS	23.3	31.40
	572	SHIP STORES+EQUIP HANDLING SYS	12.4	26.42
	573	CARGO HANDLING SYSTEMS		
	574	VERTICAL REPLENISHMENT SYSTEMS		
	580	MECHANICAL HANDLING SYSTEMS	82.4	31.17
	581	ANCHOR HANDLING+STOWAGE SYSTEMS	32.1	26.76
	582	MOORING+TOWING SYSTEMS	13.4	34.00
	583	BOATS,HANDLING+STOWAGE SYSTEMS	11.1	39.80
	584	MECH OPER DOOR,GATE,RAMP,TTBL SYS		
	585	ELEVATING + RETRACTING GEAR		
	586	AIRCRAFT RECOVERY SUPPORT SYS		
	587	AIRCRAFT LAUNCH SUPPORT SYSTEM		
*	588	AIRCRAFT HANDLING,SERVICING,STOWAGE	25.8	31.50
	589	MISC MECH HANDLING SYSTEMS		
	590	SPECIAL PURPOSE SYSTEMS	65.0	20.22
	591	SCIENTIFIC+OCEAN ENGINEERING SYS		
	592	SWIMMER+DIVER SUPPORT+PROT SYS		
	593	ENVIRONMENTAL POLLUTION CNTL SYS	11.3	11.71
	594	SUBMARINE RESC+SALVG+SURVIVE SYS		
	595	TOW,LAUNCH,HANDLE UNDERWATER SYS		
	596	HANDLING SYS FOR DIVER+SUBMR VEH		
	597	SALVAGE SUPPORT SYSTEMS		
	598	AUX SYSTEMS OPERATING FLUIDS	46.9	22.52
	599	AUX SYSTEMS REPAIR PARTS+TOOLS	6.9	18.52

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 7 - OUTFIT+FURNISHINGS WEIGHT

SWBS	COMPONENT	WT-LTON	VCG-FT
600	OUTFIT+FURNISHING,GENERAL	476.1	23.70
610	SHIP FITTINGS	12.1	41.04
611	HULL FITTINGS	2.7	32.55
612	RAILS,STANCHIONS+LIFELINES	8.3	42.52
613	RIGGING+CANVAS	1.1	51.02
620	HULL COMPARTMENTATION	103.4	21.55
621	NON-STRUCTURAL BULKHEADS	29.3	30.01

	622	FLOOR PLATES+GRATING	54.0	14.09
	623	LADDERS	12.1	25.75
	624	NON-STRUCTURAL CLOSURES	5.9	29.84
	625	AIRPORTS,FIXED PORTLIGHTS,WINDOWS	1.9	50.53
	630	PRESERVATIVES+COVERINGS	190.1	24.26
	631	PAINTING	47.1	19.93
	632	ZINC COATING		
	633	CATHODIC PROTECTION	2.7	7.00
	634	DECK COVERINGS	35.5	27.38
	635	HULL INSULATION	62.7	30.78
*	636	HULL DAMPING	18.6	4.90
	637	SHEATHING	14.0	33.31
	638	REFRIGERATION SPACES	9.4	20.43
	639	RADIATION SHIELDING		
	640	LIVING SPACES	42.4	24.05
	641	OFFICER BERTHING+MESSING	9.6	35.34
	642	NON-COMM OFFICER B+M	3.4	26.75
	643	ENLISTED PERSONNEL B+M	24.6	19.18
	644	SANITARY SPACES+FIXTURES	2.4	25.75
	645	LEISURE+COMMUNITY SPACES	2.2	23.21
	650	SERVICE SPACES	18.5	25.76
	651	COMMISSARY SPACES	8.6	25.75
	652	MEDICAL SPACES	2.2	29.02
	653	DENTAL SPACES		
	654	UTILITY SPACES	2.7	29.27
	655	LAUNDRY SPACES	3.9	21.19
	656	TRASH DISPOSAL SPACES	.8	26.75
	660	WORKING SPACES	52.1	27.98
	661	OFFICES	14.6	27.51
	662	MACH CNTL CENTER FURNISHING	1.1	15.23
	663	ELECT CNTL CENTER FURNISHING	10.3	34.06
	664	DAMAGE CNTL STATIONS	12.1	28.01
*	665	WORKSHOPS,LABS,TEST AREAS	14.1	25.03
	670	STOWAGE SPACES	52.5	16.87
	671	LOCKERS+SPECIAL STOWAGE	7.0	24.65
	672	STOREROOMS+ISSUE ROOMS	45.4	15.64
	673	CARGO STOWAGE		
	690	SPECIAL PURPOSE SYSTEMS	5.0	21.89
	698	OPERATING FLUIDS	.3	23.13
	699	REPAIR PARTS+SPECIAL TOOLS	4.7	21.82

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 8 - ARMAMENT WEIGHT

	SWBS	COMPONENT	WT-LTON	VCG-FT
	700	ARMAMENT	190.4	28.43
*	710	GUNS+AMMUNITION	53.6	38.29
	711	GUNS		
	712	AMMUNITION HANDLING		
	713	AMMUNITION STOWAGE		
	720	MISSLES+ROCKETS	101.8	24.05
*	721	LAUNCHING DEVICES	99.8	23.43
	722	MISSILE,ROCKET,GUID CAP HANDL SYS		
*	723	MISSILE+ROCKET STOWAGE	2.0	56.09
	724	MISSILE HYDRAULICS		
	725	MISSILE GAS		
	726	MISSILE COMPENSATING		
	727	MISSILE LAUNCHER CONTROL		
	728	MISSILE HEAT,COOL,TEMP CNTRL		
	729	MISSILE MONITOR,TEST,ALINEMENT		
	730	MINES		
	731	MINE LAUNCHING DEVICES		

	732	MINE HANDLING		
	733	MINE STOWAGE		
	740	DEPTH CHARGES		
	741	DEPTH CHARGE LAUNCHING DEVICES		
	742	DEPTH CHARGE HANDLING		
	743	DEPTH CHARGE STOWAGE		
*	750	TORPEDOES	13.6	35.75
	751	TORPEDO TUBES		
	752	TORPEDO HANDLING		
	753	TORPEDO STOWAGE		
	760	SMALL ARMS+PYROTECHNICS	3.0	23.75
	761	SMALL ARMS+PYRO LAUNCHING DEV	1.0	29.85
	762	SMALL ARMS+PYRO HANDLING		
*	763	SMALL ARMS+PYRO STOWAGE	2.0	20.63
	770	CARGO MUNITIONS		
	772	CARGO MUNITIONS HANDLING		
	773	CARGO MUNITIONS STOWAGE		
*	780	AIRCRAFT RELATED WEAPONS	1.8	20.40
	782	AIRCRAFT RELATED WEAPONS HANDL		
	783	AIRCRAFT RELATED WEAPONS STOW		
	790	SPECIAL PURPOSE SYSTEMS	16.6	18.93
	791	SPECIAL WEAPONS		
	792	SPECIAL WEAPONS HANDLING		
	793	SPECIAL WEAPONS STOWAGE		
	797	MISC ORDINANCE SPACES		
*	798	ARMAMENT OPERATING FLUIDS	3.6	24.40
*	799	ARMAMENT REPAIR PART+TOOLS	13.0	17.44

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

PRINTED REPORT NO. 9 - LOADS WEIGHT (FULL LOAD CONDITION)

	SWBS	COMPONENT	WT-LTON	VCG-FT
	F00	LOADS	1024.9	12.23
	F10	SHIPS FORCE	23.3	25.39
	F11	OFFICERS	3.9	25.39
	F12	NON-COMMISSIONED OFFICERS	2.2	25.39
	F13	ENLISTED MEN	17.3	25.39
	F14	MARINES		
	F15	TROOPS		
	F16	AIR WING PERSONNEL		
	F19	OTHER PERSONNEL		
	F20	MISSION RELATED EXPENDABLES+SYS	211.9	30.00
*	F21	SHIP AMMUNITION	183.5	28.87
*	F22	ORD DEL SYS AMMO	5.9	37.13
*	F23	ORD DEL SYS (AIRCRAFT)	8.0	38.11
	F24	ORD REPAIR PARTS (SHIP)		
	F25	ORD REPAIR PARTS (ORD)		
*	F26	ORD DEL SYS SUPPORT EQUIP	14.5	36.75
	F29	SPECIAL MISSION RELATED SYS		
	F30	STORES	36.2	19.31
	F31	PROVISIONS+PERSONNEL STORES	25.6	18.60
	F32	GENERAL STORES	10.6	21.05
	F33	MARINES STORES (SHIPS COMPLEM)		
	F39	SPECIAL STORES		
	F40	LIQUIDS, PETROLEUM BASED	719.9	6.57
	F41	DIESEL FUEL MARINE	663.5	6.27
*	F42	JP-5	51.7	10.98
	F43	GASOLINE		
	F44	DISTILLATE FUEL		
	F45	NAVY STANDARD FUEL OIL (NSFO)		
	F46	LUBRICATING OIL	4.5	
	F49	SPECIAL FUELS AND LUBRICANTS		

F50	LIQUIDS, NON-PETRO BASED	33.4	4.79
F51	SEA WATER		
F52	FRESH WATER	33.4	4.79
F53	RESERVE FEED WATER		
F54	HYDRAULIC FLUID		
F55	SANITARY TANK LIQUID		
F56	GAS (NON FUEL TYPE)		
F59	MISC LIQUIDS, NON-PETROLEUM		
F60	CARGO		
F61	CARGO, ORDINANCE + DELIVERY SYS		
F62	CARGO, STORES		
F63	CARGO, FUELS + LUBRICANTS		
F64	CARGO, LIQUIDS, NON-PETROLEUM		
F65	CARGO, CRYOGENIC+LIQUEFIED GAS		
F66	CARGO, AMPHIBIOUS ASSAULT SYS		
F67	CARGO, GASES		
F69	CARGO, MISCELLANEOUS		
M24	FUTURE GROWTH MARGIN		

* DENOTES INCLUSION OF PAYLOAD OR ADJUSTMENTS

APPENDIX E

MOBILITY, RANGE ASSESSMENT

Range characteristics were plotted versus ship speed for the PEM variants that were generated. This was performed to see if the drag curve shape varied significantly for the different hull sizes of the variants. Also, the effect of the shape of the sfc curve can be seen when range is plotted against speed. The range is based on running at the designated speed until all useable fuel onboard the ship is consumed. It should be kept in mind that the useable fuel onboard each variant is different.

Figure E-1 shows a range versus speed plot for the PEM variants of the Corvette. It should be noted that the diesels in the CODOG system of the baseline are running at 17 kts and below. It can be seen that no significant difference exists between the baselines and variants except for the propulsion variant at 12 knots where the range is about 10% less than the baseline.

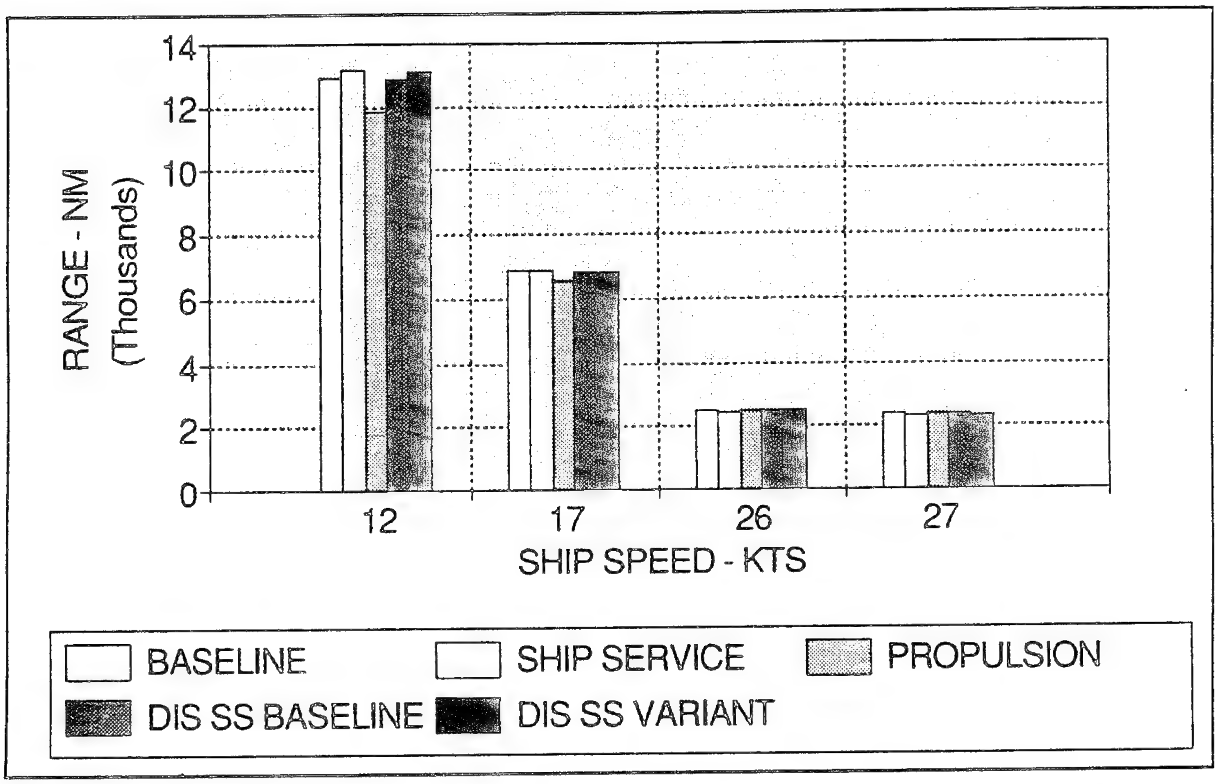


Figure E-1. Range Versus Speed - Baselines and Fuel Cell Variants - Corvette

When the fuel capacity and fuel consumption rate of the ship are examined, Figures E-2 and E-3, it can be seen that the propulsion variant has approximately 10% less fuel than the baseline & comparable or better fuel consumption. Thus, the propulsion variant is producing a comparable range for significantly less fuel.

A mission profile was generated, seen in Table E-1, for the Corvette to account for time spent at the various operating speeds. Figure E-4 shows the range of the variants using the mission profile and the useable fuel onboard (Figure E-3). Again, it can be seen that the propulsion variant is yielding comparable range for significantly less fuel.

It can be seen from Figures E-1 through E-4 that all other PEM variants of the Corvette yield comparable performance in regard to range.

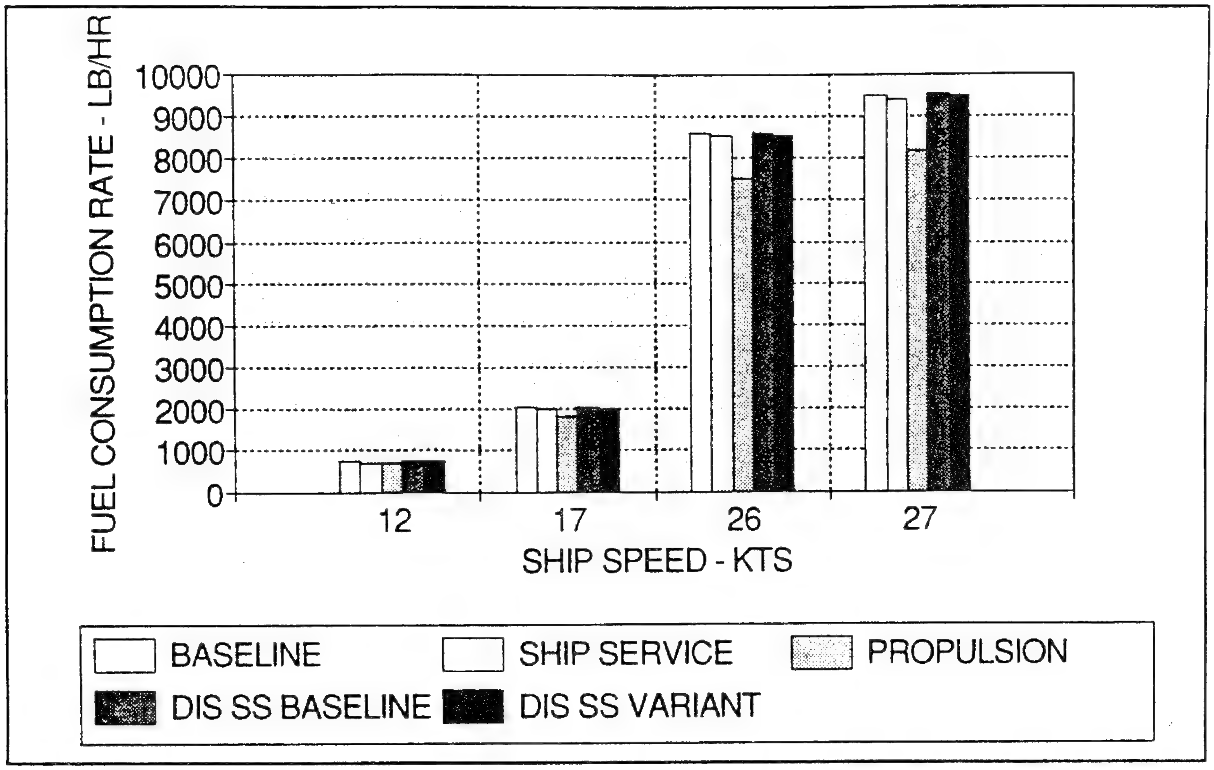


Figure E-2. Fuel Consumption Rate Versus Speed - Baselines and Fuel Cell Variants - Corvette

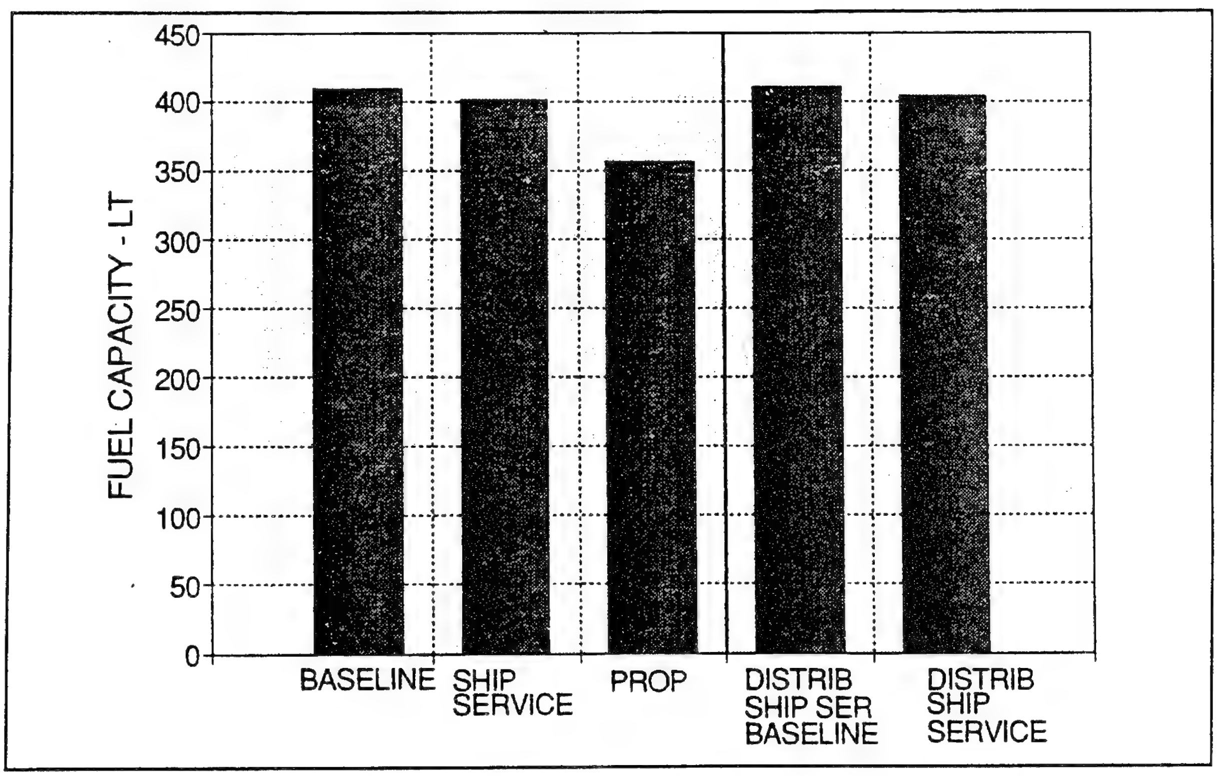


Figure E-3. Fuel Capacity - Baselines and Fuel Cell Variants - Corvette

Table E-1

Mission Profile

	Speed (kts)	Percent Time	Time (hrs)
Anchor	0	5	144
Low Speed on Diesels	12	30	864
Top Speed on Diesels	17	50	1440
Maximum Sustained on Gas Turbine	26	10	288
Top Speed on Gas Turbine	27	5	144
Total/Average	16.05	100	2880
NOTE: Four months deployment.			

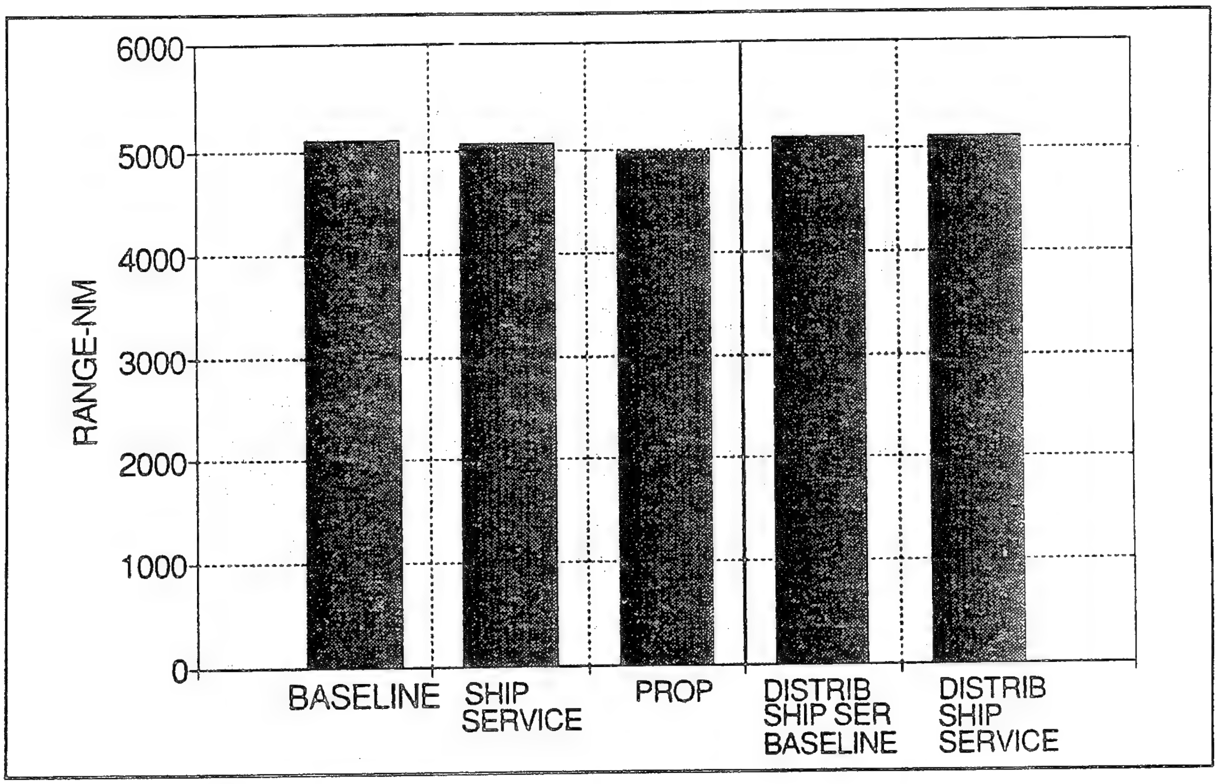


Figure E-4. Mission Profile Range - Baselines and Fuel Cell Variants

Figure E-5 shows a range versus speed plot for the PEM variants of the Destroyer. It can be seen that the range of the propulsion variant is about 5% less than the baseline at the higher speeds and the difference is negligible at 20 knots. At even lower speeds, the propulsion variant does better. This indicates that the sfc curve for the PEMFC is flatter at smaller load fractions than that of the ICR gas turbines in the baseline. The fuel consumption rate for the propulsion variant is actually less for all the speeds shown as can be seen in Figure E-6. The reason for the lower range is the smaller fuel capacity of the variant (shown in Figure E-7, about 5% less than baseline). A mission profile was also generated for the Destroyer and is shown in Table E-2. The range of the propulsion variant, using the mission profile,

is included in Figure E-8. The improvement over the baseline is very significant and is largely contributed to by the replacement of the inefficient standby gt plant.

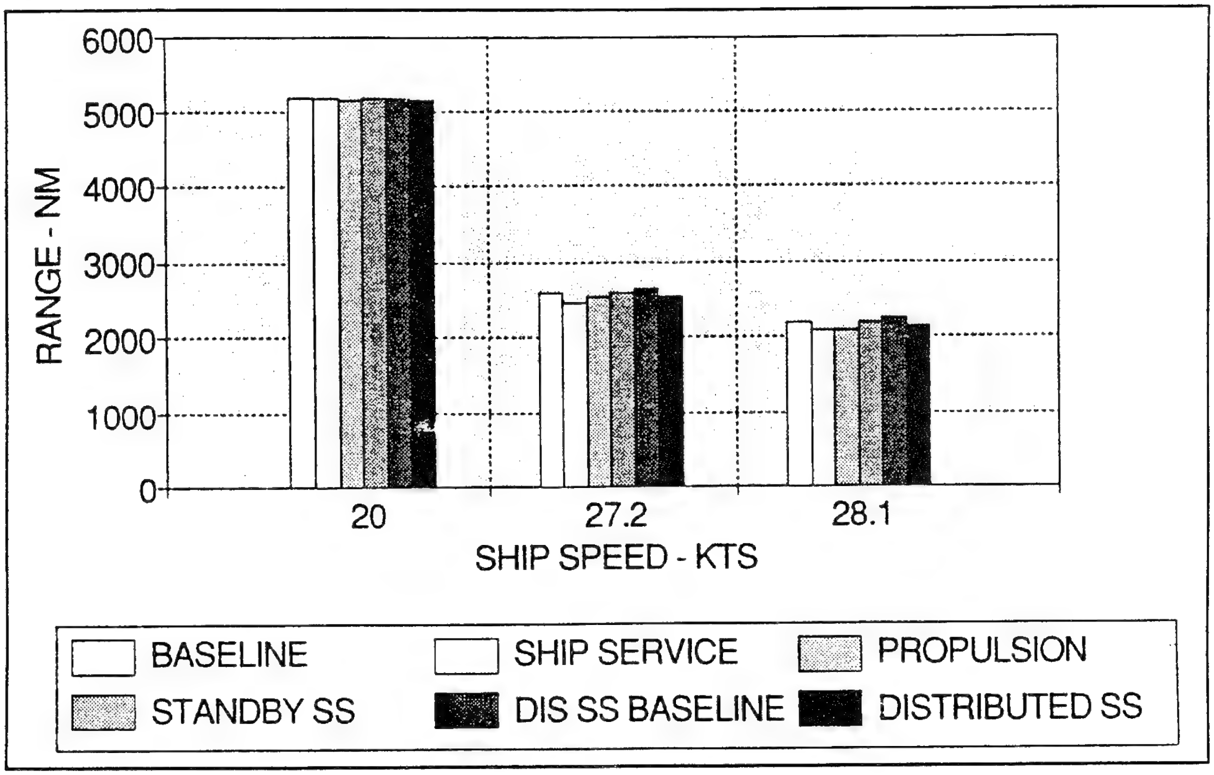


Figure E-5. Range Versus Speed - Baselines and Fuel-Cell Variants - Destroyer

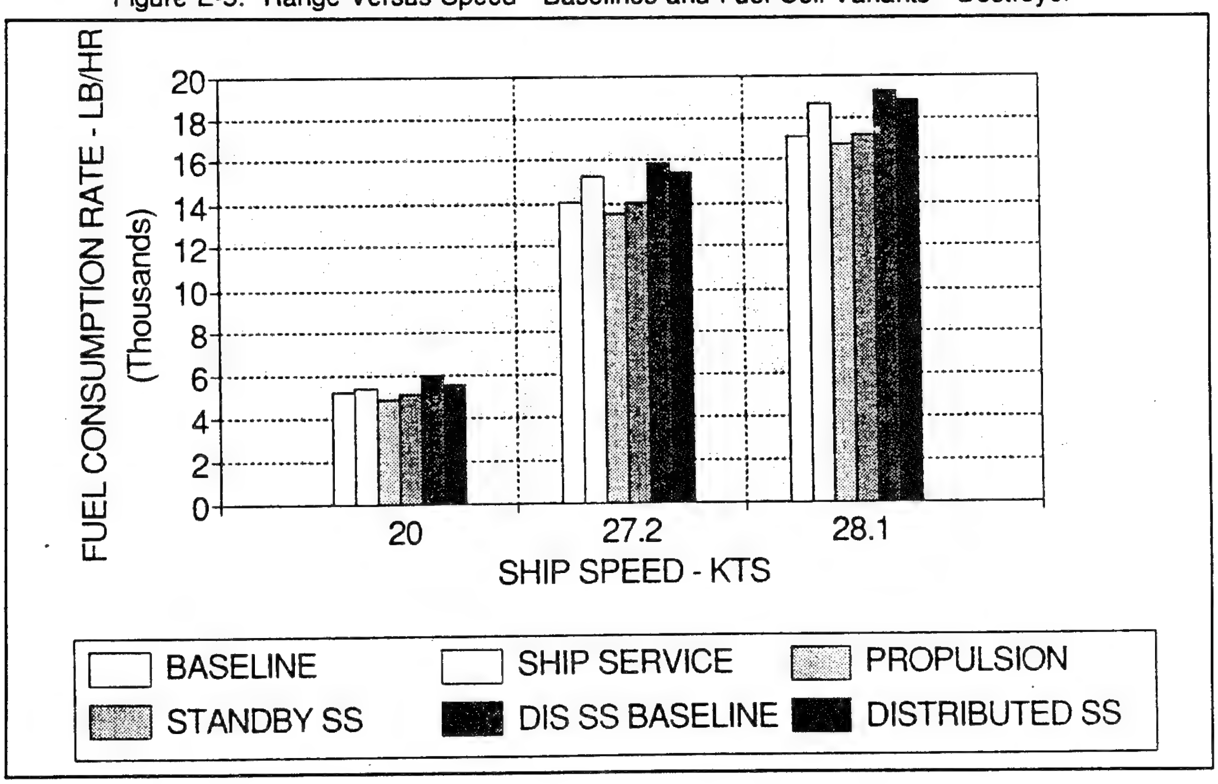


Figure E-6. Fuel Consumption Rate Versus Speed - Baselines and Fuel Cell Variants - Destroyer

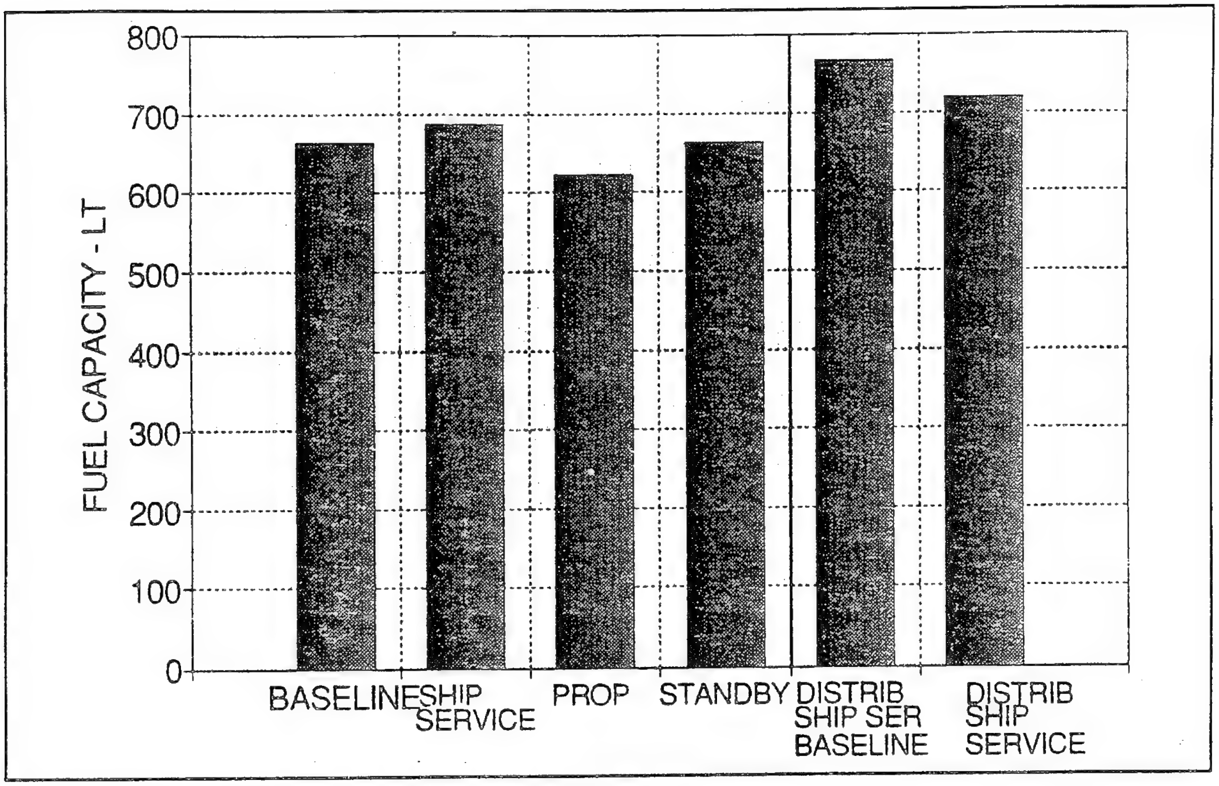


Figure E-7. Fuel Capacity - Baselines and Fuel Cell Variants - Destroyer

Table E-2

Destroyer Mission Profile

2700 Hours Underway 1500 Hours at Anchor	
While Underway:	
Speed	Percent of Time
11.0	27.2
15.0	28.7
19.0	37.3
23.0	4.5
27.0	2.3
NOTE: Six month deployment.	

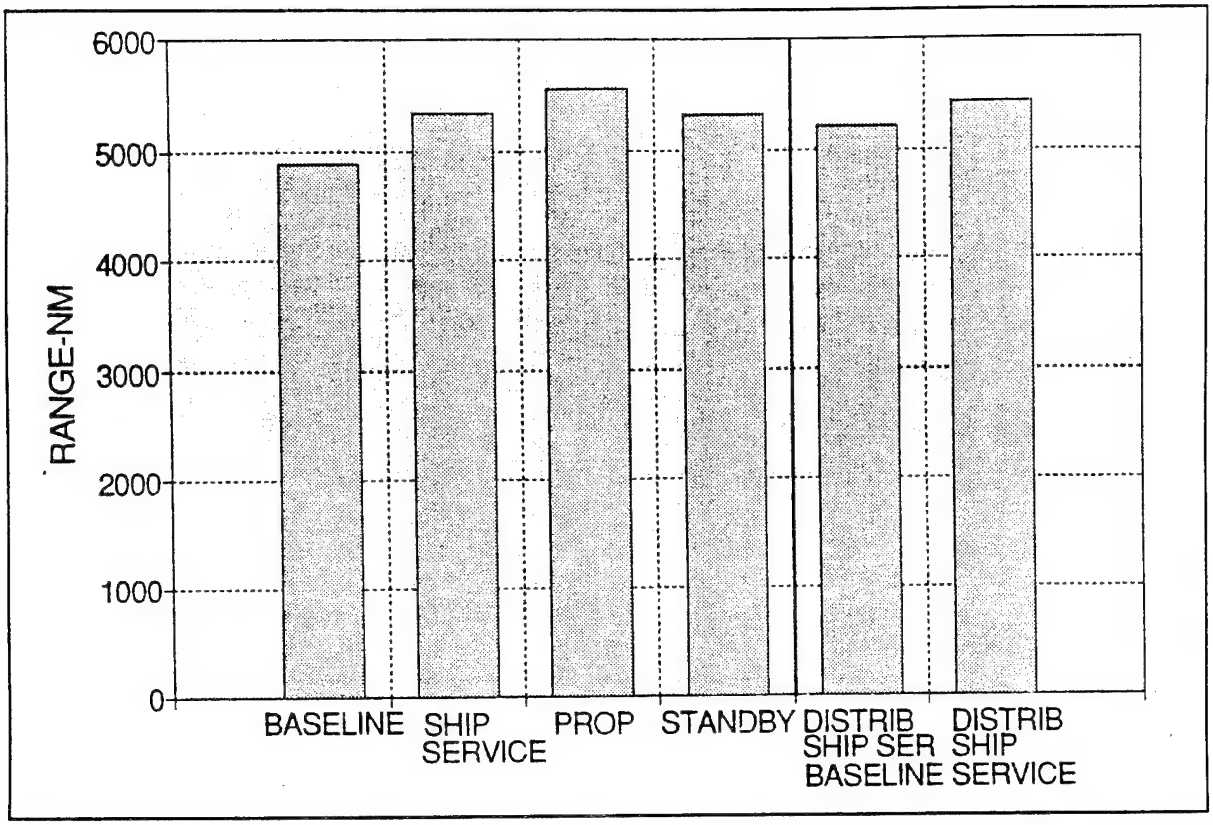


Figure E-8. Mission Profile Range - Baselines and Fuel Cell Variants - Destroyer

No difference in range is seen in Figure E-5 when the standby variant of the Destroyer is compared with the baseline. This is because the standby generator is typically not running when the ship is underway. In Figure E-8 the mission profile is used to calculate range with the useable fuel onboard, it can be seen that a significant increase in range is afforded from the replacement of the gas turbine standby generator by a PEMFC plant.

The range of the ship-service variant, as seen in Figure E-5, is about 10% less than that of the baseline. This is due to the higher fuel consumption rate as seen in Figure E-6. The rate is higher, in part, due to configuration rather than technology. The PDSS system on the baseline is providing very efficient ship-service power from the ICR gas turbines at high load fractions as compared to the dedicated PEM plants. Also, the PEM plants are replacing the PDSS generators and thereby a surplus in propulsion power exists, thus extra speed. It can be seen that as speed decreases, the range of the ship-service variant, Figure E-5, is more comparable with the baseline. The increase in range that is seen in Figure E-8, with the mission profile being used, can be attributed largely in part to the replacement of the standby gas turbine plant.

Figures E-5 through E-8 show comparable performance between the distributed ship service baseline and variant of the Destroyer.

In order to compare the ship service application of fuel cells against a more conventional and aptly replaceable system, a DDG-51 baseline was studied (uses gas turbine generators). The effect of a direct backfit, without ship redesign, of PEM fuel cell technology was sought. Figures E-9 and E-10 show the range calculated at a constant speed and for a mission profile for the DDG baseline and variant. It can be seen that the PEMFC is out-performing the gas turbines at smaller load fractions and that a very significant benefit is manifest when the mission profile is used. The fuel consumption rates are shown in Figure E-11 and since a backfit scenario is used, the fuel capacities are the same.

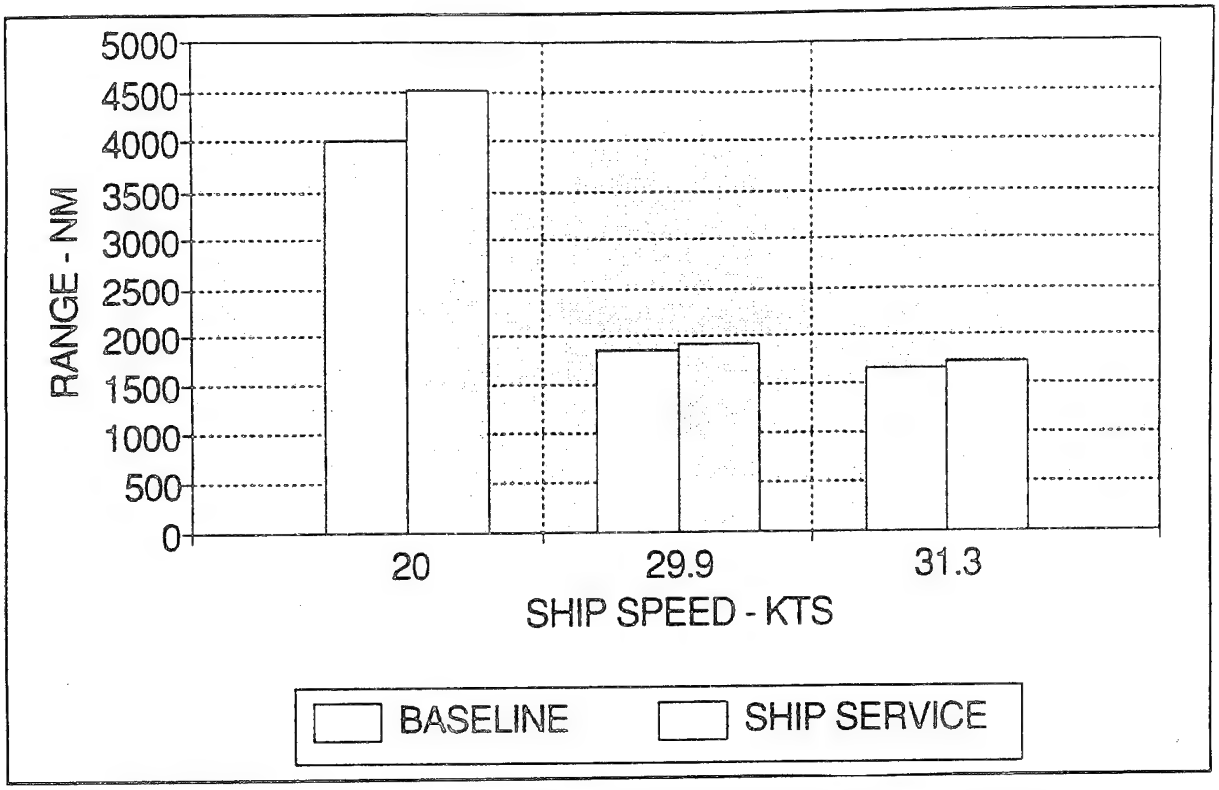


Figure E-9. Range Versus Speed - Baseline and Fuel Cell Variant - DDG-51

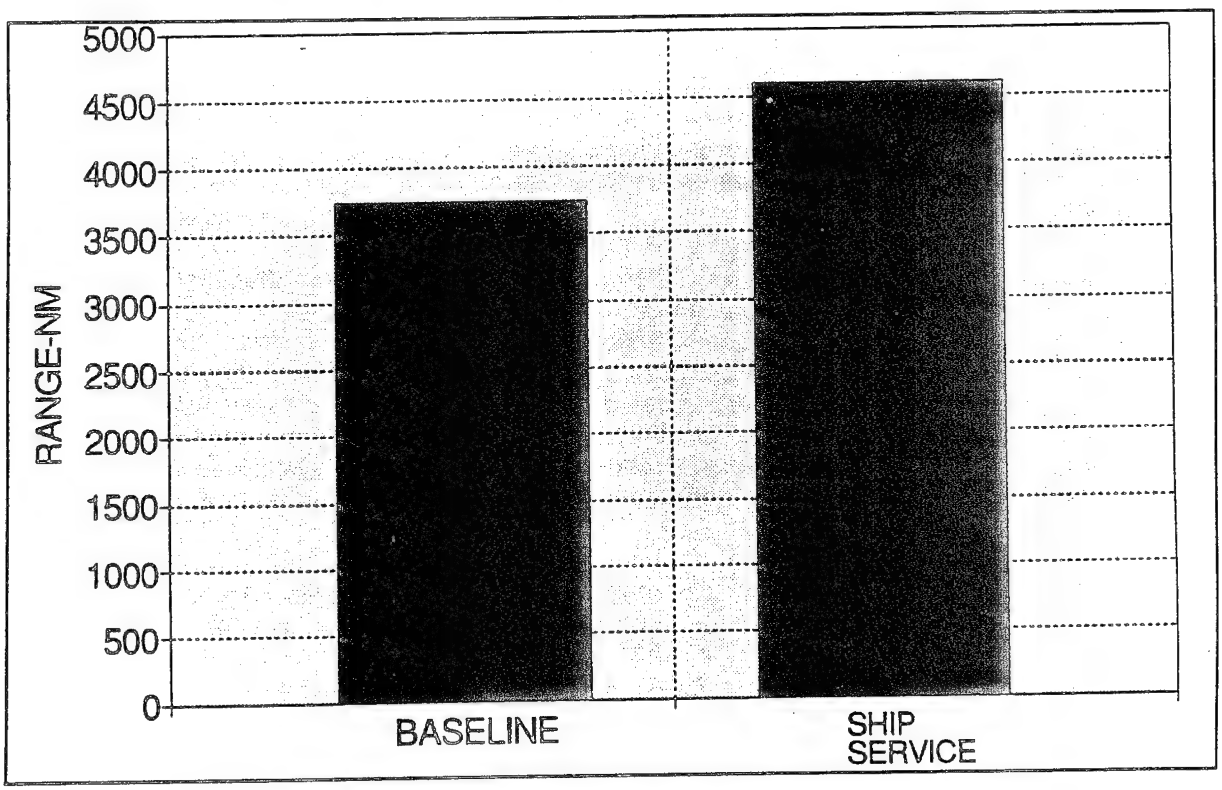


Figure E-10. Mission Profile Range - Baselines and Fuel Cell Variants

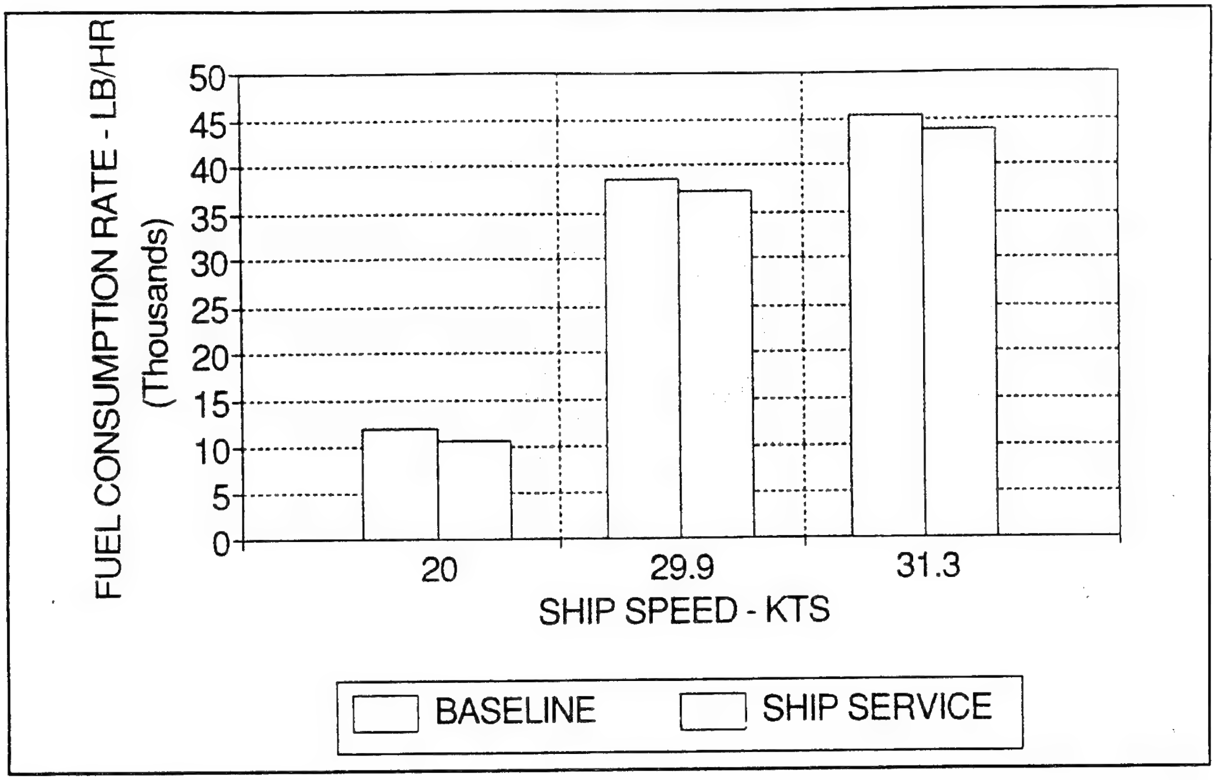


Figure E-11. Fuel Consumption Rate Versus Speed - Baseline and Fuel Cell Variant - DDG-51

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APPENDIX F

OVERVIEW OF COST ESTIMATING METHODS

The information enclosed in this appendix are excerpts from Reference 2, customized to be made consistent with this study. Table F.1 is a summary of various cost categories studied.

ASSESSING COST DELTAS: dC

In the cost optimized design approach, shown in Figure 12, a new technology is introduced into the Baseline ship, and a Variant ship is synthesized under the following conditions:

(1) The life cycle cost is allowed to vary, i.e., the cost impacts of the technology are assessed.
(2) All performance areas are held constant.

The change in life cycle cost between the Baseline ship and the cost-optimized Variant ship is measured by the cost delta, designated by the term "dC" where

$$dC = NPV(AC_{Variant} + O\&S_{Variant}) - NPV(AC_{Baseline} + O\&S_{Baseline})$$

and NPV, Net Present Value, indicates a time correction for the cash flows associated with the two cost components, Acquisition Cost (AC) and the total Operating and Support costs (O&S). All terms in the above equation are discussed below.

ACQUISITION COST (AC)

In this study, Acquisition Cost is defined as

$$AC = \text{End Cost} + \text{Expendables Cost}$$

where

End Cost = the total, lead ship acquisition cost

Expendables Cost = the total acquisition cost of expendable munitions

The Expendables Cost is set at zero for this stage in the study and, therefore, the terms Acquisition Cost and End Cost are interchangeable. Acquisition Cost is described in more detail in Tables F.1, F.2, F.3 and F.6.

End Cost is estimated using a NSWC version of the Naval Sea Systems Command (NAVSEA) Unit Price Analysis (UPA) cost model as discussed in Reference 27. The technical characteristics represented in the Baseline ship UPA cost model are typical of an "Arleigh Burke" class guided missile destroyer (DDG-51); the NAVSEA cost model was modified to reflect variations in the system composition of the Propulsion and/or Electric Plant. For Variant ships, i.e., those incorporating new technologies, acquisition End Costs were estimated as follows:

(1) Labor and material cost implications of the new technology are determined,
(2) The Baseline ship cost model is modified accordingly.
(3) The Variant ship cost model is exercised, and the lead ship acquisition cost is estimated.

BASIC CONSTRUCTION COST (BCC)

When estimating ship acquisition cost, ten categories are considered, as shown in Table F.2 and defined in Table F.3. Of these ten categories, Basic Construction/Conversion (BCC) is the heart of the estimate as (1) it represents the labor and material required to construct the ship, and (2) several of the other cost categories are calculated as a fraction of the BCC as summarized in Table F.6.

For this study, the NAVSEA 017 Unit Price Cost Analysis (UPA) Model was used to estimate the Basic Construction/Conversion cost. Based on shipbuilder submitted bids and return costs, a UPA cost model estimates acquisition cost at any level of SWBS detail (typically 2 or 3-digit SWBS) using the following algorithms:

$$\text{Cost}_i = (\text{Labor Cost}_i + \text{Overhead Cost}_i) + \text{Material Cost}_i$$

$$\text{Labor Cost}_i = \text{PRD}_i * \text{Lc} * (\text{Hr/Lt})_i * \text{\$/Hr} * \text{Lt}_i$$

$$\text{Overhead Cost}_i = \text{OH Rate} * \text{Labor Cost}_i$$

$$\text{Material Cost}_i = \text{INF}_i * (\text{\$/Lt})_i * \text{Lt}_i$$

where

PRD	=	shipyard productivity factor,
INF	=	material inflation correction factor,
Lc	=	unit labor learning curve factor,
$/Hr	=	labor hourly rate,
Lt	=	weight in long tons,
OH Rate	=	labor overhead rate, and
i	=	refers to the ith SWBS group.

Two of the more critical variables are

Hr/Lt	=	Labor cost estimating relationship and
$/Lt	=	Material cost estimating relationship.

in as much as these two variables define the labor and material cost "characteristics", based on technological characteristics, for any given SWBS group.

OPERATING AND SUPPORT COST (O&S)

O&S costs are defined and tracked by NAVSEA 017 in four major cost areas:

(1) Direct Unit
(2) Intermediate Maintenance
(3) Depot Maintenance
(4) Indirect Operating Support

Table F.4 summarizes the O&S expenditure information included within each of these four categories. Fiscal year summaries of this information are published each March by NAVSEA 017 for all Navy ships in active commissioned status throughout the entire reporting fiscal year.

Yearly operating and support costs are estimated using the NAVSEA 50C O&S cost model. This cost model uses direct calculations along with a scaling/analogy approach to estimate O&S costs for the above four cost categories (and associated sub-categories) shown in Table F.5. Also shown in Table F.5 are the direct calculations and analogies assumed for this study. The method proceeds as described below.

(1) O&S cost breakouts of a similar ship class are obtained from the VAMOSC-SHIPS data base, References 23 and 24. The Destroyer Baseline O&S cost estimates were scaled from the "Spruance" class of destroyers (DD-963) because of its technical similarity to the Destroyer Baseline ship. Most of the Corvette Baseline O&S cost estimates were scaled from the "Oliver Hazard Perry" class of guided-missile frigates (FFG-7) because of its technical similarity to the Corvette Baseline ship. The Corvette's Depot Maintenance

costs, required in greater detail, were scaled from the "Brooke" class of guided-missile frigates (FFG-1).

(2) Direct cost calculations are made where all needed information is known, e.g.,

(a) Direct Unit, Personnel Cost

$$= \frac{\text{Variant ship number of personnel}}{\text{Baseline ship number of personnel}} * \text{Pay Rate}$$

(b) Direct Unit, Fuel Cost

$$= \text{Barrels of fuel consumed per year} * \text{Cost per barrel of fuel}$$

Note: FY93 cost for Navy diesel fuel = 53.13 US$
(Source: POM 94 Cost Guidance, 17 Jan 92)

(3) Scaling analogies for the various other O&S cost categories are selected. Scaling may be a function of the one-digit SWBS weight distribution, hull volume, installed shaft horsepower, total crew number, or fuel usage. Scaling ratios are typically calculated as a function of the Variant ship value to the Baseline ship value, e.g.,

Direct Depot Maintenance (Hull) Cost Scaling Ratio

$$= \frac{\text{Variant Hull Volume}}{\text{Baseline Hull Volume}} * \text{Baseline Depot Maintenance (Hull)}$$

(4) The O&S cost model is exercised, and the yearly operating and support costs are estimated.

(5) The total Operating and Support Cost over a 30 year ship life is calculated as

$$\text{Total O\&S} = 30 * \text{Yearly Operating and Support Costs}$$

NET PRESENT VALUE OF COST (NPV)

When calculating dC for the purpose of making an economic comparison between the Baseline ship and the Variant ship, Reference 28 suggests the comparison be made in terms of the present value of the total Acquisition cost and the total Operating and Support cost. The Net Present Value (NPV) is calculated using an assumed cash flow for the two cost components and a 4.5% discount factor (4.5% has been specified for most Government investments by Office of Management & Budget (OMB) Circular No. A-94 and for most DoD investments by DODINST 7041.3).

For this study, the following cash flows were assumed:

Acquisition costs for each follow ship are expended in one lump sum with construction taking two years following the lump sum payment. For each lead ship, the cost for "Plans" are disbursed in one lump sum at the time of ship authorization and construction costs are funded the following year. Lead ship construction is completed three years from the time of ship authorization.

Operating and support costs for each ship begin once construction is completed and the ship is delivered, i.e., AC expenditures have ceased, and O&S costs continue in equal increments for thirty years.

With these assumptions made, the present value of the total life cycle cost (LCC) is calculated:

$$NPV(LCC) = NPV(AC) + NPV(30 * \text{yearly O\&S})$$

Table F.1

Definitions of Cost Categories (Definitions from "NAVSEA Ship Cost Estimating Handbook, August 1992)

I. **Research, Development, Test and Evaluation (RDT&E) Cost:** The total cost of all studies conducting research, tests and evaluations geared to assist in the engineering design and development process of a particular ship.

II. **Basic Construction Cost (BCC):** The original contract award price for ship construction (or modification/conversion as appropriate). The government categorizes BCC into nine major ship "functional areas", the Ship Work Breakdown Structure (SWBS). Each SWBS category has an associated cost estimating relationship (CER) for materials and labor, e.g., cost per ton, pay rate, overhead rate.

SWBS Category:		
Group 100	=	Hull Structure
Group 200	=	Propulsion Plant
Group 300	=	Electric Plant
Group 400	=	Command and Surveillance
Group 500	=	Auxiliary Systems
Group 600	=	Outfit and Furnishings
Group 700	=	Armament
Margin		
Group 800	=	Integration/Engineering
Group 900	=	Ship Assembly & Support Services
Profit and Facility Cost of Money		

III. **Ship Acquisition Cost** (also commonly referred to as "Ship End Cost"): The total ship cost signified by the Navy's budget line item, i.e., Shipbuilder and Construction, Navy (SCN) appropriation, which is the sum of the costs from the following major category codes (MCC):

MCC 111/113	=	Construction Plans
MCC 211	=	Basic Construction
MCC 311/312	=	Change Orders
MCC 400	=	GFM Electronics *
MCC 900	=	GFM Ordnance/Air
MCC 525	=	GFM Hull, Mechanical & Electrical
MCC 521	=	GFM Propulsion
MCC 800	=	Other Support
MCC 541	=	Test and Instrumentation
MCC 533	=	Stock Shore-Based Spares
MCC 951	=	Program Manager Reserve
MCC 953	=	Contract Escalation
* Note: GFM	=	Government Furnished Material

IV. **Operating and Support (O&S) Cost:** Encompasses costs associated with items such as ship manning, fuel consumption, maintenance and overhauls over the life of the ship.

V. **Life Cycle Cost (LCC):** The total cost to the government of acquisition and ownership of a system over its full life. This encompasses all past, present and future costs. These costs include development, procurement, operation, support and, as appropriate, disposal.

VI. **Net Present Value (NPV) - derived from Life Cycle Cost:** The value today of future benefits or costs. The present value of a stream of expenditures is determined by multiplying each year's expected annual benefit or cost by its appropriate discount factor (a discount factor converts future dollars to present dollars or value) and then summing the results over all the years of the period of the alternative being considered. Inflation is generally excluded from the present value analysis.

Table F.2

Shipbuilding and Conversion Navy (SCN) Breakout

Shipbuilder Related Costs	
Plans	
Basic Construction / Conversion =	SWBS 100, Hull Structure
Change Orders	SWBS 200, Propulsion Plant
Escalation	SWBS 300, Electric Plant
	SWBS 400, Command & Surveillance
	SWBS 500, Auxiliary Systems
	SWBS 600, Outfitting & Furnishing
	SWBS 700, Armament
	Margin
	SWBS 800, Engineering
	SWBS 900, Assembly
	Profit
	Facility Cost of Money
Combat Systems / GFE Costs	
Electronics	
HM&E	
Ordnance	
Propulsion	
Other Costs	
Other	
Project Managers Growth	

Summation = End Cost	

Table F.3

Shipbuilding and Conversion Navy (SCN) Category Definitions

Shipbuilder Related Costs

Plans = Cost of non-recurring detailed construction plans, including related engineering calculations, computer programs, contractor-responsible technical manuals, damage control books, ship's selected records, and mock-ups. The lead ship normally bears the burden of these costs.

Basic Construction/Conversion = All allowable labor, overhead, and shipbuilder-furnished material costs, including the cost for installing GFE, plus an amount for the facility cost of money.

Change Orders = Costs associated with state-of-the-art improvements, drawing corrections, drawing/ship specification mismatches, incorporation of safety items, fleet directed improvements, shipbuilder repair/modification of GFE, and delivery point changes.

Escalation = Shipbuilder reimbursements due to inflation during the life of the contract.

Profit = A percentage of Basic Construction/Conversion.

Facility Cost of Money = Costs associated with shipbuilder facility investments. A percentage of Basic Construction/Conversion.

Combat Systems / GFE Cost and Other Costs

Electronics GFE = Hardware and software costs associated with electronic production components, training support equipment, test and engineering services, and repair parts associated with installation.

Ordnance GFE = Hardware and software costs associated with fire and missile control systems, search radars, missile launching systems, gun systems, training support equipment, test and integration services, and other ordnance equipment.

Propulsion GFE = Cost for nuclear reactors, cores, turbines, gears, and other selected items. Normally used only for nuclear powered ships.

HM&E GFE = Hardware and software costs associated with HM&E equipment, HM&E deep submergence systems, small boats, special vehicles, environmental protection equipment, training support equipment, HM&E engineering services, repair parts associated with HM&E equipment installation, and all medical equipment provided by the Naval Medical Command.

Other = Costs for Planned Maintenance Subsystems, equipment transportation, travel in support of ship acquisition, contract engineering services, commissioning ceremonies, in-house engineering services, and SUPSHIP material.

Project Managers Growth = The Project Manager's contingency fund for unforeseen future problems or actions.

Table F.4

Operating and Support Costs Breakout
(Visibility and Management of Operating and Support Costs-SHIPS)

1.0	Direct Unit Costs - Personnel, Fuel, Material, Purchased Services
2.0	Direct Intermediate Maintenance - Afloat and ashore labor and material for maintenance
3.0	Direct Depot Maintenance - Scheduled overhauls, non-scheduled repairs, fleet modernization, other depot
4.0	Direct Recurring Investment - Exchanges, organizational issues
5.0	Indirect Operating and Support - Training, publications, engineering technical services, ammo handling, non-O&MN costs

Table F.5

Operating and Support Cost Categories and Scaling Analogies

Cost Category		O&S Scaling Analogies
Direct Personnel		
1.1.1.2	Officers	Number, Pay Rate
1.1.1.3	Enlisted	Number, Pay Rate
1.1.2	TAD	Total Crew Number
Unit Operations		
1.2.1.1	Fuel	Barrels/Year, Fuel Cost
1.2.1.2	Other POL	Barrels/Year
1.2.2	Repair Parts	Lightship Weight
1.2.3	Supplies	Total Crew Number
1.2.4	Training Expendable Stores	None
1.2.5.1	Organizational Exchanges	None
1.2.5.2	Organizational Issues	Lightship Weight
1.3	Purchased Services	Total Crew Number
Direct Maintenance		
2.0	IMA	Installed Shaft Horsepower
3.0	Depot Maint (Hull)	Depot Maint (Hull)
3.0	Depot Maint (Propulsion)	Depot Maint (Propulsion)
3.0	Depot Maint (Other)	Depot Maint (Other)
Indirect Costs		
4.1	Training	Total Crew Number
4.2	Publications	Total Crew Number
4.3	Engineering & Technical Services	Total Crew Number
4.4	Ammunition Handling	None
	Retirement	35% of Direct Pay

Table F.6

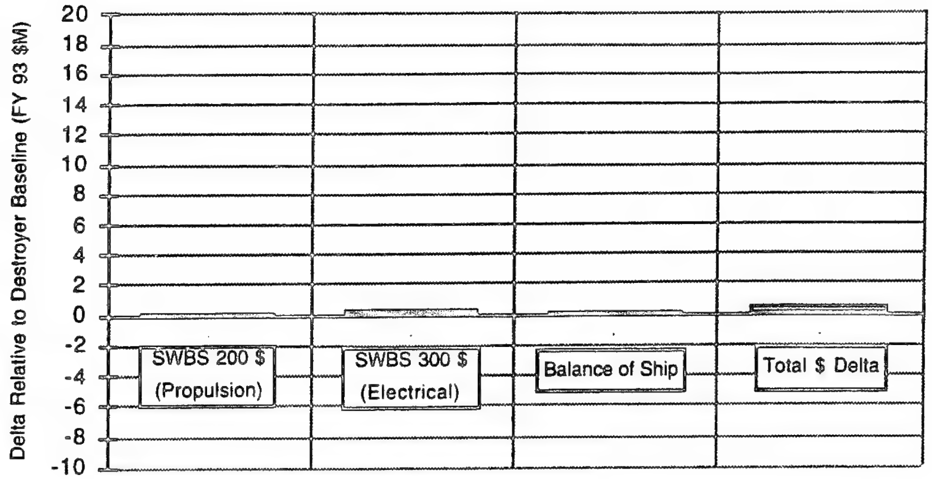
Acquisition Cost Category Relationships to Basic Construction/Conversion

Shipbuilder Related Costs	
Plans =	Estimated independently
Basic Construction / Conversion = (BCC)	Estimated via (a) the UPA model, (b) Manufacturing Complexities, and (c) Vendor Quotes
Change Orders =	10% BCC, Lead Ship 5% BCC, Follow Ships
Escalation =	0 for constant dollar estimates
Combat Systems / GFE Costs	
Electronics =	0 for this study
HM&E =	0 for this study
Ordnance =	0 for this study
Propulsion =	0 for this study
Other Costs	
Other =	8.6% BCC, Lead Ship 6.5% BCC, Follow Ships
Project Managers Growth =	4% All above categories less Escalation, Lead ship 3% All above categories less Escalation, Follow ships
Summation = End Cost	

APPENDIX G

FIGURES DEMONSTRATING FUEL CELL SYSTEM IMPACTS ON BASIC CONSTRUCTION COST

Figure 1a. Lead Destroyer BCC Deltas using PEM fuel cell system:
Standby Ship Service Power Variant *



* Lead Baseline Destroyer BCC is estimated at 317 million dollars (FY93$)

Figure 1b. Cost driver comparison of Destroyer Baseline versus Variant:
Standby Ship Service Power using PEM fuel cell system (FY 93$M)

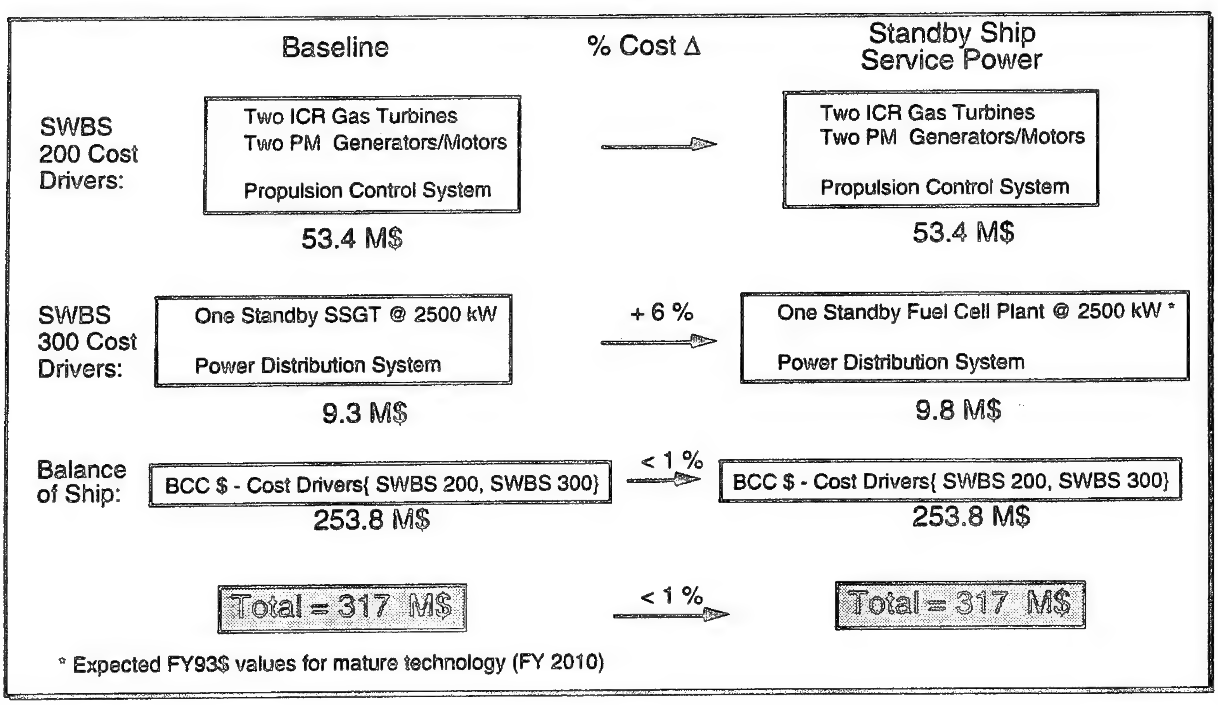
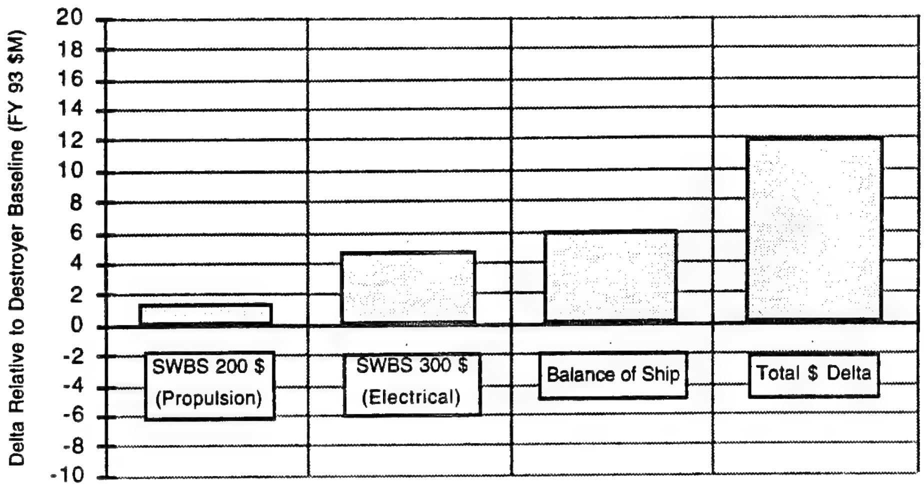


Figure 2a. Lead Destroyer BCC Deltas using PEM fuel cell systems: Direct Replacement Ship Service Power Variant *



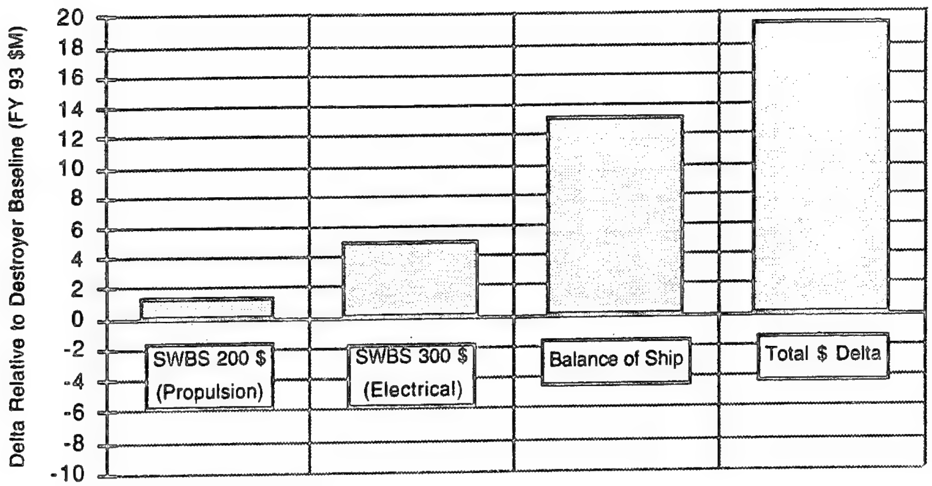
* Lead Baseline Destroyer BCC is estimated at 317 million dollars (FY93$)

Figure 2b. Cost driver comparison of Destroyer Baseline versus Variant: Direct Replacement Service Power using PEM fuel cell systems (FY 93$M)

	Baseline	% Cost Δ	Direct Replacement Ship Service Power
SWBS 200 Cost Drivers:	Two ICR Gas Turbines Two PM Generators/Motors Propulsion Control System 53.4 M$	→	Two ICR Gas Turbines Two PM Generators/Motors Propulsion Control System 53.4 M$
SWBS 300 Cost Drivers:	One Standby SSGT @ 2500 kW Power Distribution System 9.3 M$	+ 54 % →	Three PEM Fuel Cell Plants @ 2500 kW each * Power Distribution System 14.3 M$
Balance of Ship:	BCC $ - Cost Drivers{ SWBS 200, SWBS 300} 253.8 M$	+ 2 % →	BCC $ - Cost Drivers{ SWBS 200, SWBS 300} 259.8 M$
	Total = 317 M$	+ 4 % →	Total = 328 M$

* Expected FY93$ values for mature technology (FY 2010)

Figure 3a. Lead Destroyer BCC Deltas using PEM fuel cell systems: Distributed Ship Service Power Variant *



* Lead Baseline Destroyer BCC is estimated at 317 million dollars (FY93$)

Figure 3b. Cost driver comparison of Destroyer Baseline versus Variant: Distributed Ship Service Power using PEM fuel cell systems (FY 93$M)

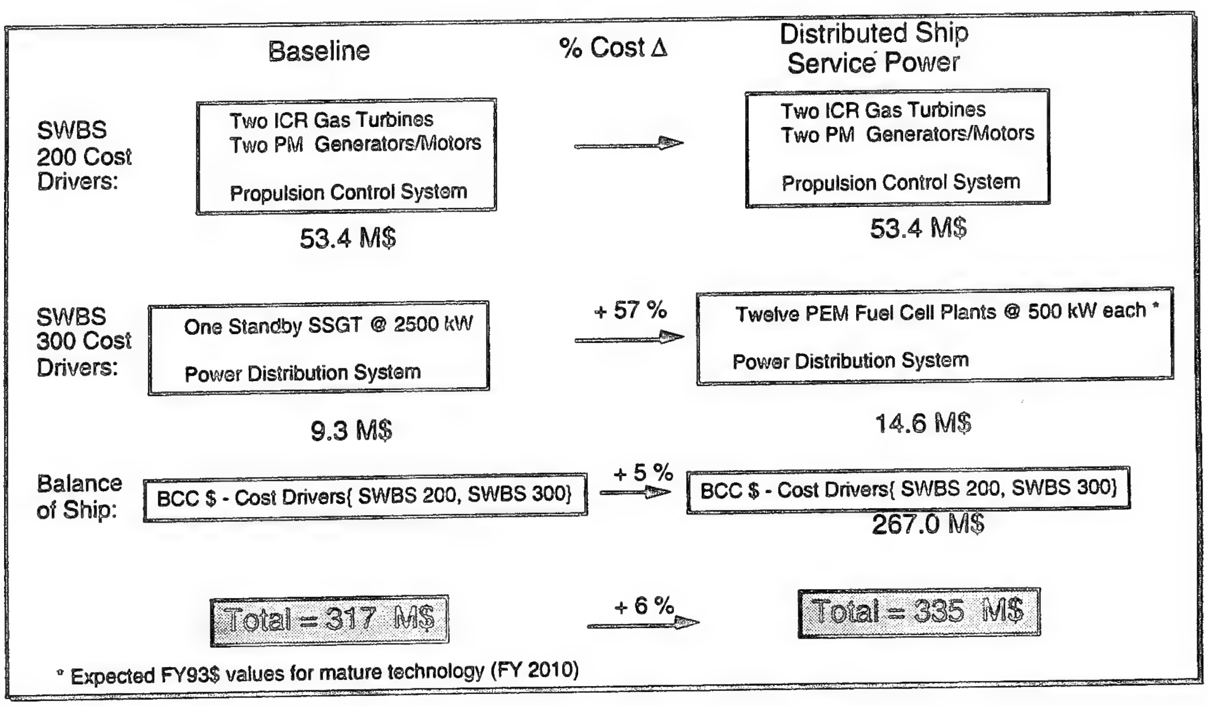
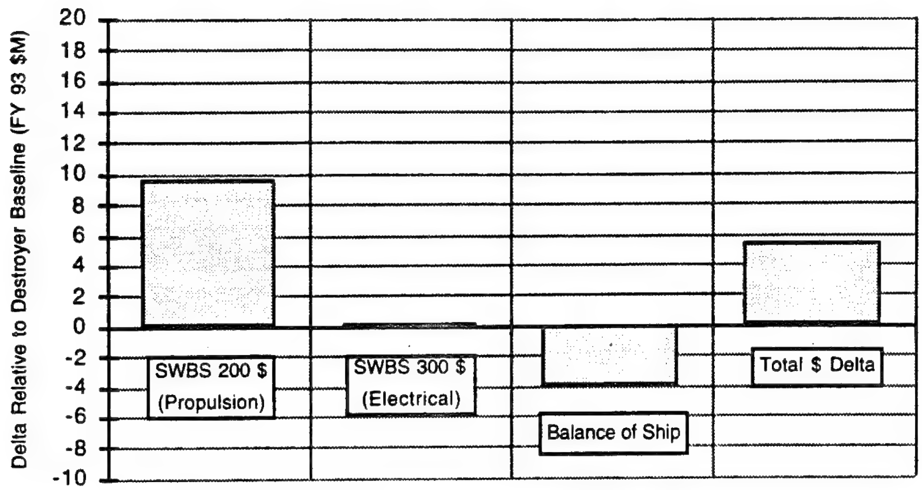


Figure 4a. Lead Destroyer BCC Deltas using PEM fuel cell systems: Direct Replacement Propulsion Power Variant *



* Lead Baseline Destroyer BCC is estimated at 317 million dollars (FY93$)

Figure 4b. Cost driver comparison of Destroyer Baseline versus Variant: Direct Replacement Propulsion Power using PEM fuel cell systems (FY 93$M)

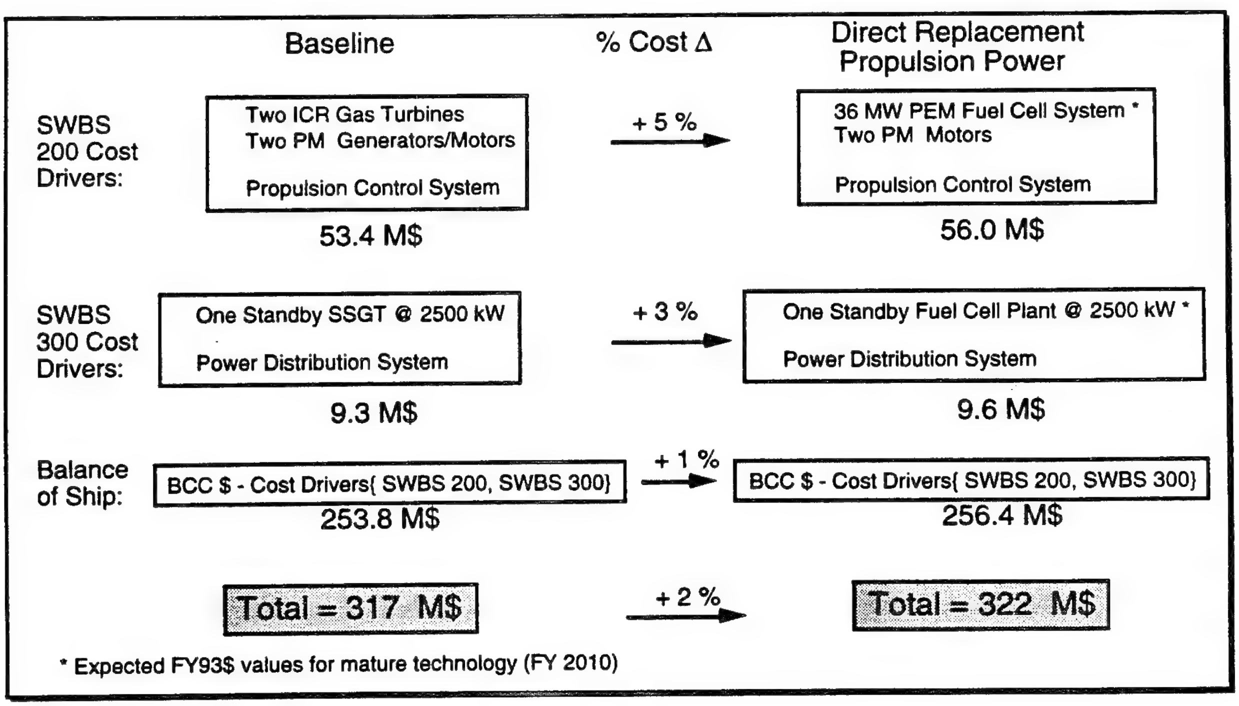
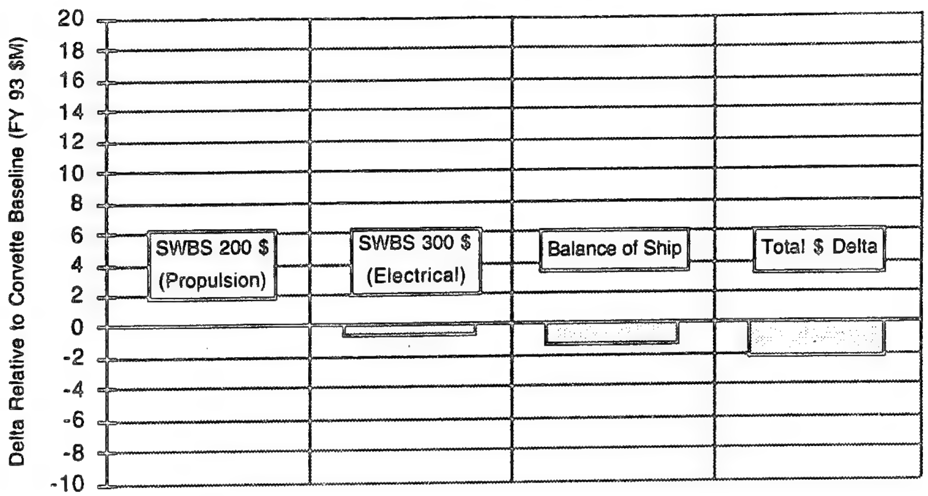


Figure 5a. Lead Corvette BCC Deltas using PEM fuel cell systems: Direct Replacement Ship Service Power Variant *



* Lead Baseline Corvette BCC is estimated at 116 million dollars (FY93$)

Figure 5b. Cost driver comparison of Corvette Baseline versus Variant: Direct Replacement Ship Service Power using PEM fuel cell systems (FY 93$M)

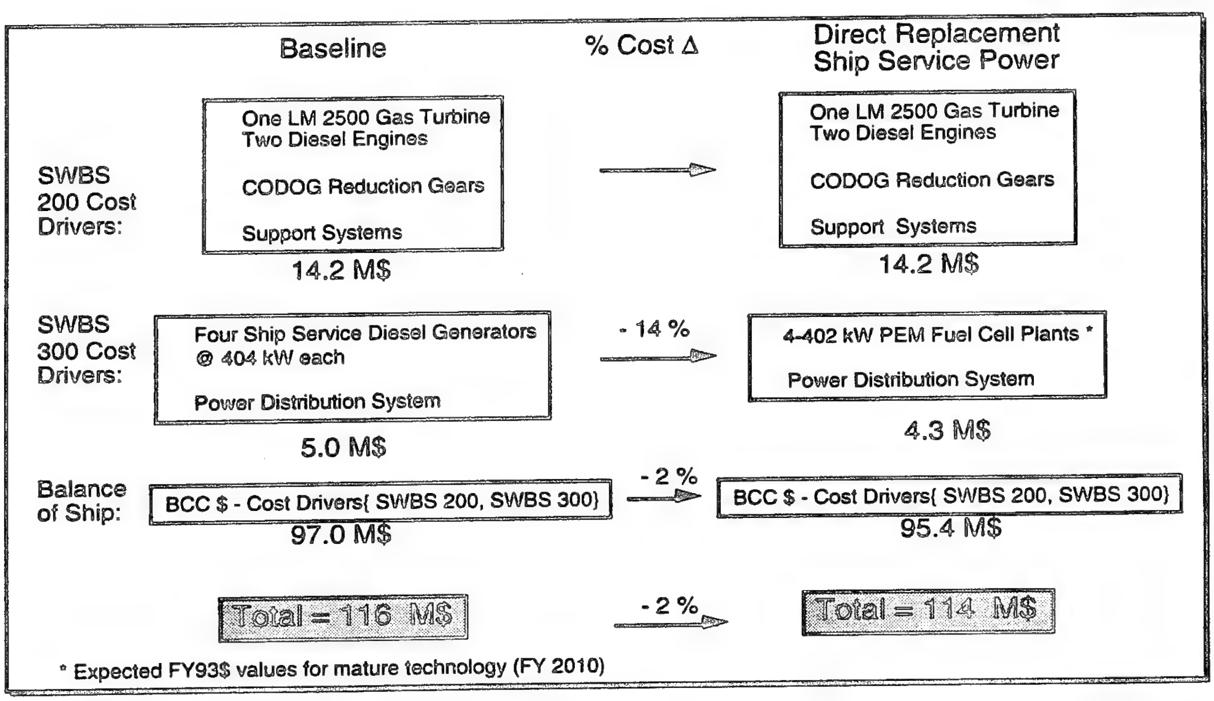
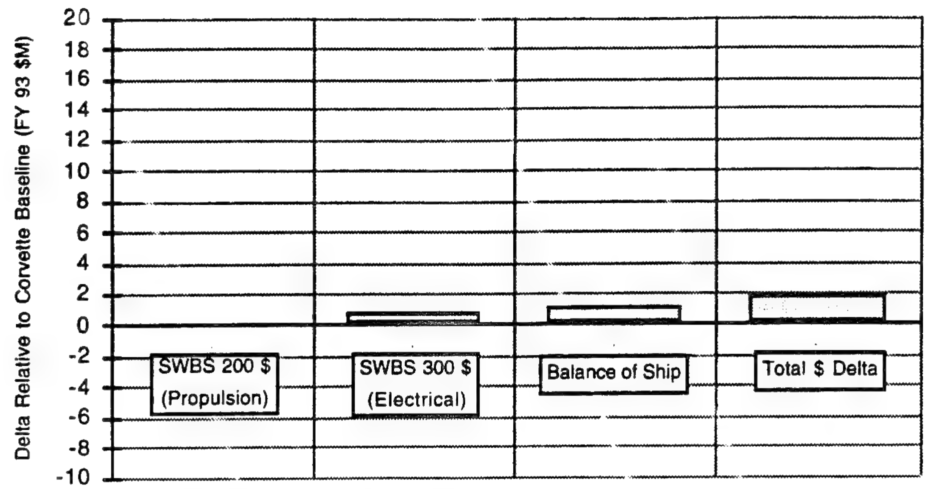


Figure 6a. Lead Corvette BCC Deltas using PEM fuel cell systems: Distributed Ship Service Power Variant *



* Lead Baseline Corvette BCC is estimated at 116 million dollars (FY93$)

Figure 6b. Cost driver comparison of Corvette Baseline versus Variant: Distributed Ship Service Power using PEM fuel cell systems (FY 93$M)

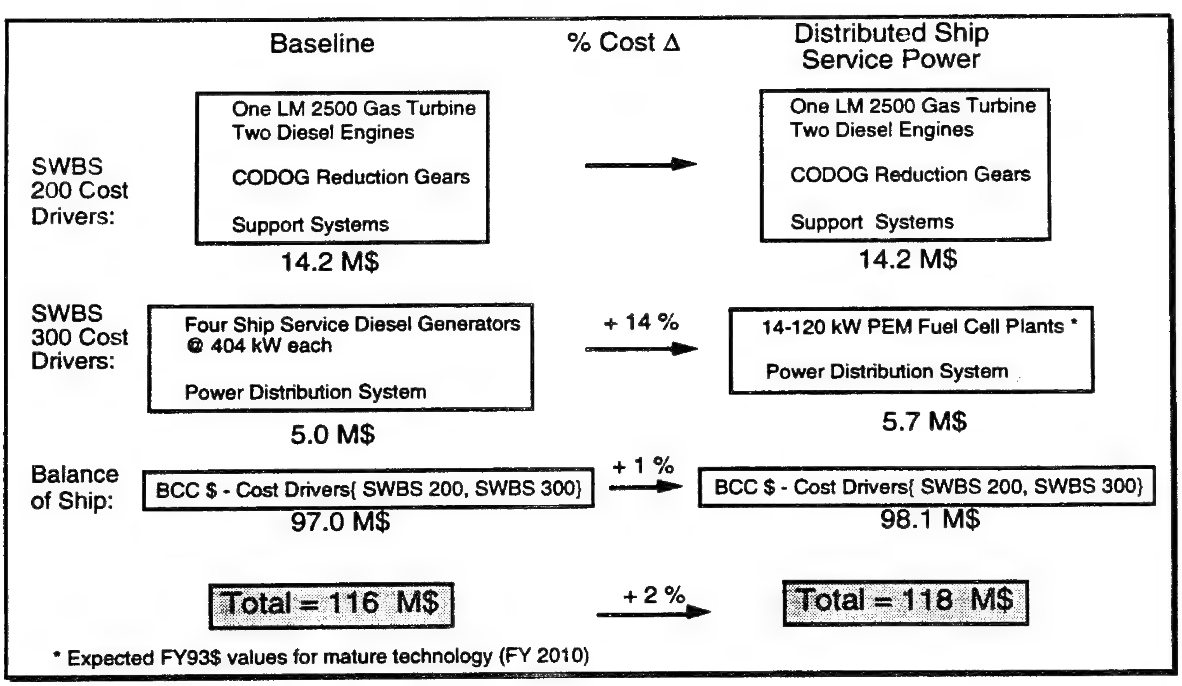
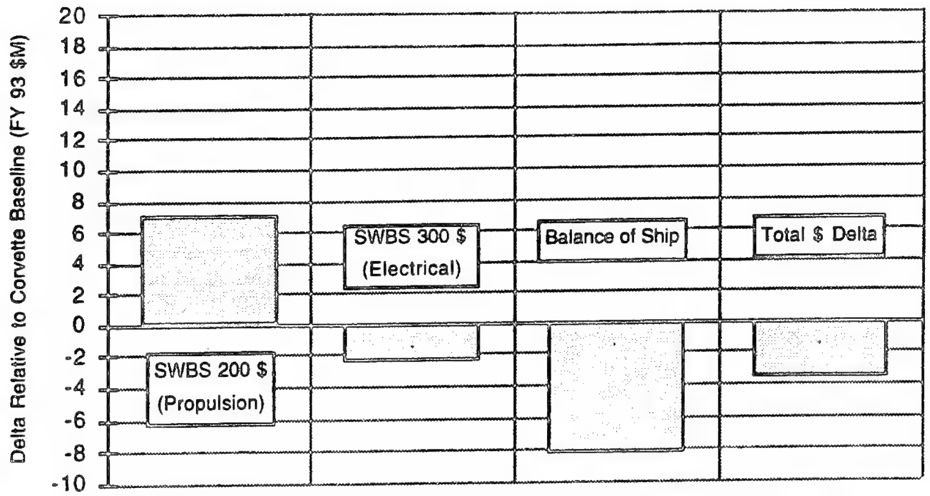
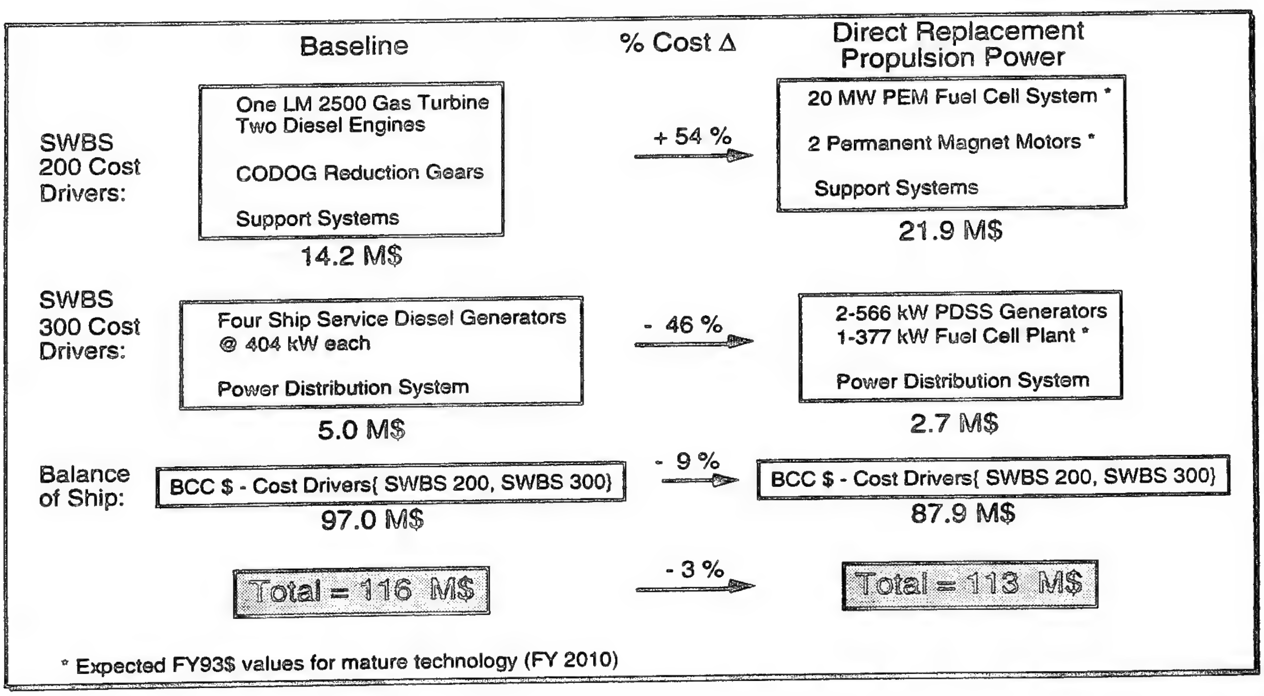


Figure 7a. Lead Corvette BCC Deltas using PEM fuel cell systems: Direct Replacement Propulsion Power Variant *



* Lead Baseline Corvette BCC is estimated at 116 million dollars (FY93$)

Figure 7b. Cost driver comparison of Corvette Baseline versus Variant: Direct Replacement Propulsion Power using PEM fuel cell systems (FY 93$M)



APPENDIX H

FIGURES DEMONSTRATING FUEL CELL SYSTEM COST DRIVERS

Figure 1a. Proton Exchange Membrane (PEM) fuel cell system: Fuel cell stack and Balance of Plant (BOP) - Percent cost of overall system for 15 samples

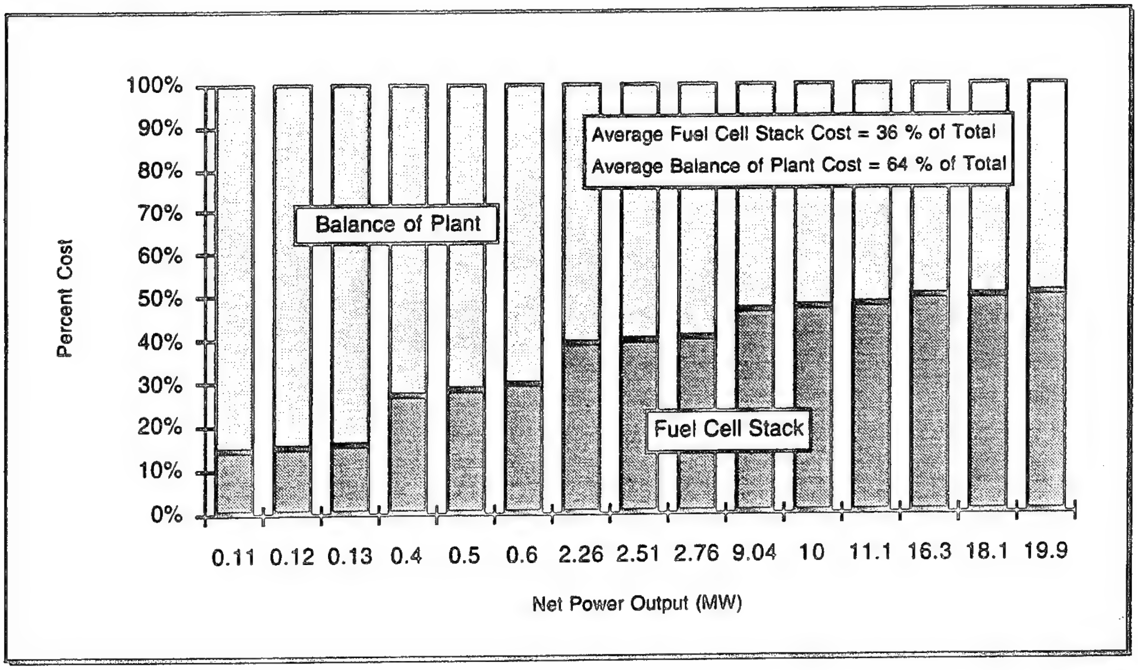


Figure 1b. Molten Carbonate fuel cell system at 1 atmosphere (MC1): Fuel cell stack and Balance of Plant (BOP) - Percent cost of overall system for 12 samples

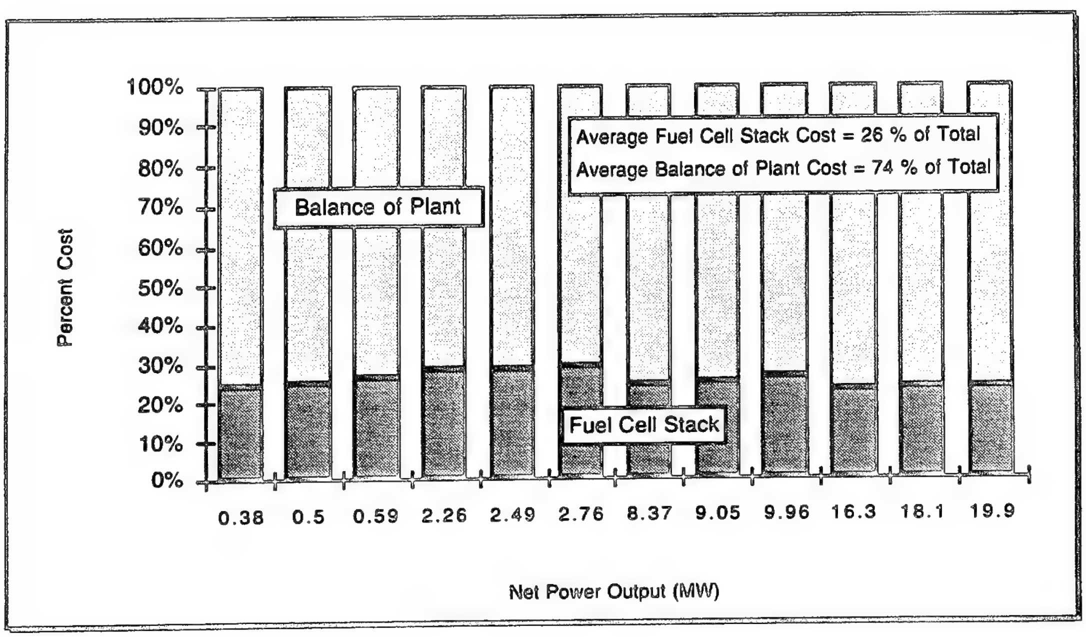


Figure 1c. Molten Carbonate fuel cell system at 6 atmospheres (MC6): Fuel cell stack and Balance of Plant (BOP) - Percent cost of overall system for 12 samples

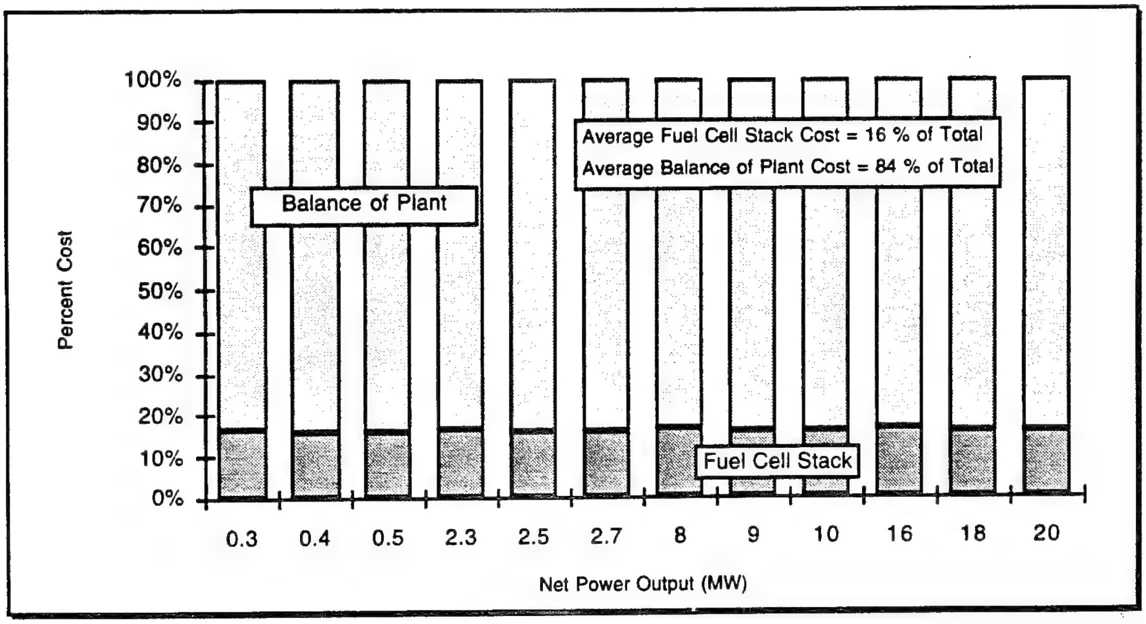
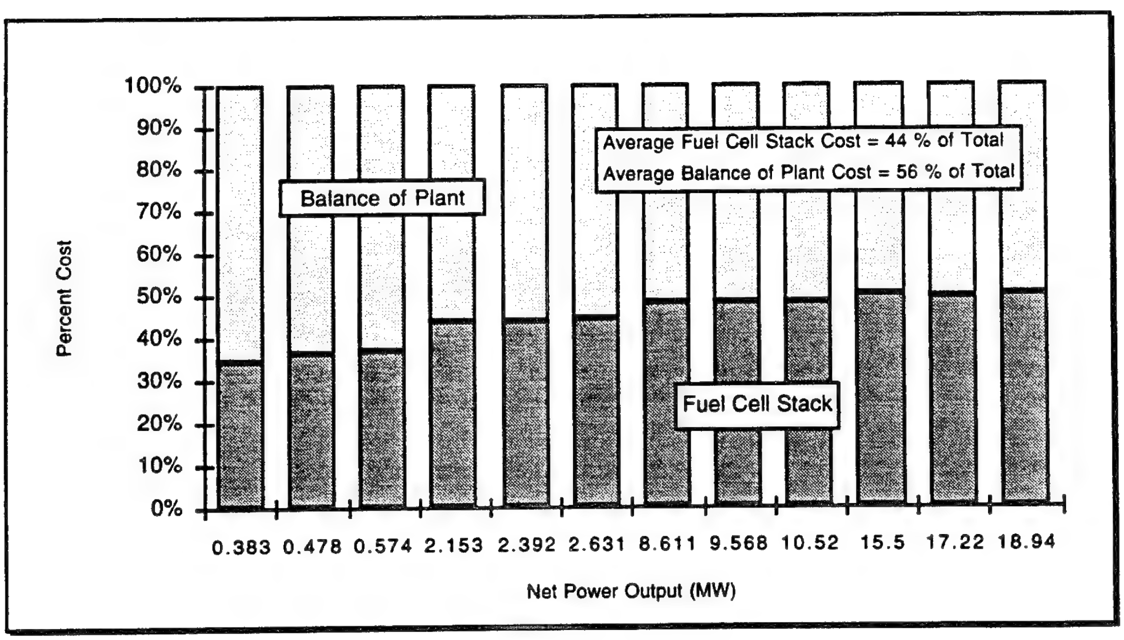


Figure 1d. Phosphoric Acid fuel cell system (PA): Fuel cell stack and Balance of Plant (BOP) - Percent cost of overall system for 12 samples



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APPENDIX I

OVERVIEW OF WEIGHT ANALOGY AND MANUFACTURING COMPLEXITY

One very common approach used to estimate the cost of an item is analogy. Analogy involves using the known cost and characteristics of an item, the reference, to estimate the cost of another similar item. The item's characteristics include its physical dimensions, weight and volume, and its performance characteristics, which include parameters such as power, speed, flow rate, and the type of technology. Establishing the best logical parameter to estimate the cost is the responsibility of the cost analyst.

The most common parameter used for the analogy method is the weight (cost per unit weight). This method assumes that the cost is linear with respect to weight. For small weight changes, this method will provide reasonable estimates; however, it neglects changes in power and packaging densities, types of technology, and many other factors.

The weight based analogy method involves determining the cost per pound of the reference item, which is usually expressed in dollars per pound ($/LB). The cost per pound of the reference item is then multiplied by the weight of the new item in order to estimate the estimated cost of the new item.

The weight based analogy method significantly overestimates the reduction in the labor portion of the cost when an item is reduced in weight. The converse is true for when an item is increased in weight.

Changes to the weight of an item's integral parts does not reduce the machine tool set-up time or the time to perform quality control inspections and tests. The assembly time and the packaging or shipping preparation time may only be slightly effected by changing the weight of an items integral parts.

Another cost assessment technique commonly used involves a parametric cost model. PRICE-H is a computerized cost estimating model, developed by General Electric, that estimates cost using a parametric approach. Parameters such as weight, quantity, schedule, design inventory and the fabrication process are used by the model.

One of the fundamental variables used by the PRICE-H model is the Manufacturing Complexity. The Manufacturing Complexity is the technology index; a separate Manufacturing Complexity is used to define both the structural and electronic portion of an assembly.

The Manufacturing Complexity is a measure of an item's:

(1) technology;
(2) its producibility (material, machining and assembly tolerances, machining difficulty, surface finish, etc.);
(3) yield;
(4) platform (specification level, operating environment, and the reliability requirements associated with that environment); and
(5) all labor required to produce the item.

The PRICE-H model can be used to determine the Manufacturing Complexity of an item that is to be used as the reference. When the reference items: weight, volume, specification level, production cost, and the start date for production, are inputs to the model, the item's Manufacturing Complexity can determined. General Electric and many users of the model have found that similar items have very similar Manufacturing Complexities when they are designed to operate in the same environment (i.e.. specification level).

Using this relationship, it is possible to estimate the cost of a new item, if a Manufacturing Complexity value can be determined for a reference item. The PRICE-H documentation lists typical values of Manufacturing Complexity for a wide variety of items, and a complexity generator is available, when it is difficult to locate a suitable reference.

The PRICE-H model will provide accurate cost estimates even when the reference item is considerably different in size from the item under consideration. However, when large differences in size are present,

the author believes that the Manufacturing Complexity should be modified to reflect this difference. This belief is supported by the model's complexity generator. The inputs required for the complexity generator are as follows: the machining precision, the type of material, the difficulty of assembly, the number of parts, and the specification level.

When an item is reduced in size, the primary inputs for the complexity generator remain the same. This will produce the same Manufacturing Complexity; however, one parameter that will change is the distance over which the machining precision must be maintained. Reductions in size will reduce this distance, which will in turn reduce the Manufacturing Complexity slightly. There is no specific rule for determining the amount that the Manufacturing Complexity should change with respect to changes in size.

Figure I.1 shows how the acquisition cost of an item changes with respect to changes in weight assuming that the same technology is used throughout. Both the weight based analogy and the constant Manufacturing Complexity method of estimating the cost change are shown. It can be seen that the constant Manufacturing Complexity method produces results that are non-linear with respect to changes in weight. These two curves provide the upper and lower bound of cost for an item based on a reference.

Depending upon the type of technology and the difference in weight between the two items under consideration, a decision as to which method is most applicable has to be made. Weight differences between new ship designs and the existing DDG-51 baseline were not considered to be large enough to force modification of the Manufacturing Complexity. Therefore, for the majority of the Baseline and Variant ship analysis, Manufacturing Complexities were used to estimate ship item costs.

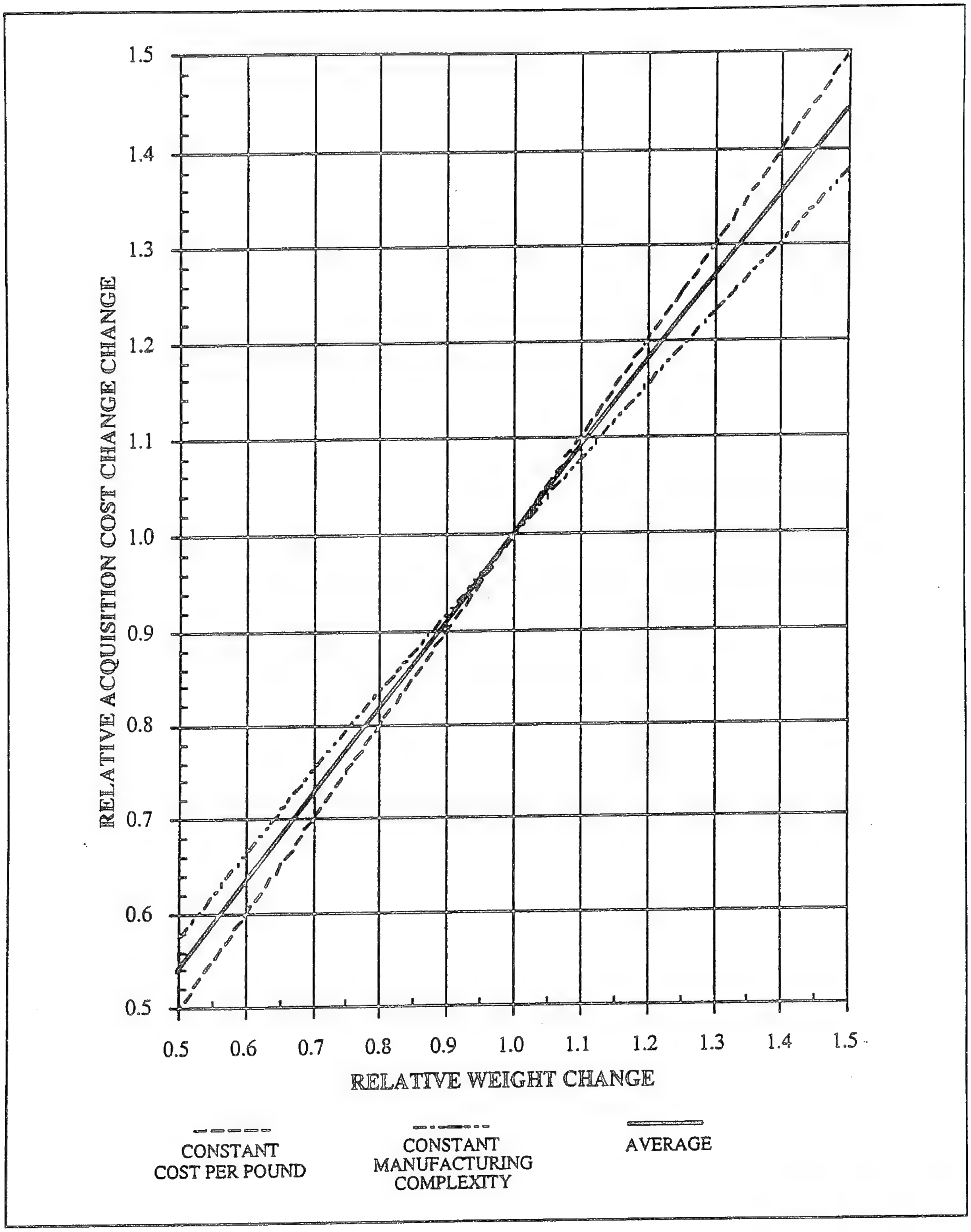

Figure I.1. Relative Acquisition Cost Change With Respect to Changes in Weight for Components Using Similar Technology

APPENDIX J

DETAILED APPROACH FOR COST ESTIMATES

The acquisition cost estimating method initiates with a 3-digit UPA cost model of a DDG-51 "Arleigh Burke" class guided-missile destroyer. The technical characteristics represented in each Baseline ship concept are typical of a DDG-51 except SWBS 200 and 300, the Propulsion Plant and Electric Plant, respectively. CERs were slightly modified for SWBS 200 and 300 systems to better reflect the unique characteristics of each Baseline. With the technical characteristics of each Baseline and Variant ship established, the cost assessment procedure is summarized as follows:

Cost Estimation of Baseline Ship Concepts, Destroyer and Corvette

All cost estimates were made for a theoretical first (T1) ship and escalated to FY93 dollars. A 90% Learning Rate was used to convert all levels of T1 costs to First Follow ship costs.

A. Basic Construction Cost:

(1) Using the latest DDG-51 class weight-breakdown and CERs, provided by NAVSEA 017, costs for the DDG-51 class systems were estimated. Ship cost estimates were calculated to the one-digit level for the entire ship except for SWBS Groups 200 and 300, which were estimated to the three digit level.

(2) DDG-51 class system costs were converted to Manufacturing Complexities, MCPLXs, using algorithms developed from the PRICE-H model. Manufacturing Complexities are estimated at the 1-digit level of detail for SWBS groups 100 and 400 through 900; at the 3-digit level of detail for SWBS groups 200 and 300; and for the Margin. More details on Manufacturing Complexities may be found in Appendix I.

(3) Destroyer and Corvette Baseline designs were received from CDNSWC 214 and BLA, respectively.

(4) Baseline concepts costs were estimated by applying "DDG-51 derived" MCPLXS factors to the weights of those Destroyer and Corvette systems resembling respective DDG-51 type systems.

(a) All Destroyer and Corvette SWBS groups 100 and 400 through 900 were assumed to have the same MCPLXS, to the 1-digit level, as respective DDG-51 SWBS groups.

(b) SWBS groups 200 and 300, estimated down to the 3-digit level, were assumed to have many systems with the same MCPLXS as respective DDG-51 class systems.

(i) Cost estimates for several Baseline systems, although similar to corresponding DDG-51 systems, were elicited from various sources instead of using DDG-51 derived MCPLXS. These updated costs, considered to be the most accurate available, replaced corresponding MCPLXS-derived cost estimates.

(ii) Labor and material cost implications of unique or new technologies, i.e., those systems not inherent to a DDG-51 class, are determined. Several sources are used to assess the implications; interviews with experts most knowledgeable with the new technology are invaluable in this step.

(iii) These primary systems and their sources are summarized in Table J-1.

Table J-1

Sources for Cost Estimates of Destroyer and Corvette Systems Which Have Cost Updates, Newer Technologies or Systems Not Inherent to the DDG-51 Class*

Destroyer Baseline Concept		
SWBS	Description	Source
234	ICR Gas Turbines	Newport News Study for DDS IPS, April 1993
235	Electronic Propulsion	Newport News Study for DDS IPS, April 1993
245	Propulsors	Newport News Study for DDS IPS, April 1993
252	Propulsion Control System	Newport News Study for DDS IPS, April 1993
314	Power Conversion Equipment	Newport News Study for DDS IPS, April 1993
Corvette Baseline Concept		
SWBS	Description	Source
233	Diesel Engines	GEC Alsthon, Paxman Diesels, Proposal Report
234	LM-2500 Gas Turbine	FY 1991 DTRC IED Study
241	Reduction Gears	FY1993 Cincinnati Gear Company Labor and Overhead from 1990 WLB Study
243	Shafting	Labor and Overhead from 1990 WLB Study
*This table lists the sources of only those systems designed within each Baseline ship's Propulsion Plant (SWBS 200) and Electric Plant (SWBS 300).		

(5) PEM fuel cell system costs were estimated. They represent the total sum of the costs to manufacture and install the BOP, stack and desulfurizers. BOP and stack costs were calculated by multiplying the given cost per kilowatt estimates by the associated kilowatt rating. Desulfurizer cost estimates were based upon vendor quotes.

(a) Cost per kilowatt estimates for the BOP and stack were provided for the PEM, MC and PA fuel cell systems. These estimates were generated by CDNSWC 2724 from a cost model developed by Analytic Power Inc.

(b) Power ratings for each BOP and stack ranged from 120 kW to 18 MW, depending on the fuel cell application and ship type.

(c) The cost for each sub-system, the BOP and stack, was generated by multiplying its kilowatt rating by its respective cost per kilowatt.

(d) The cost per kilowatt for the PEM desulfurizer units were calculated from Molten Carbonate system costs taken from FY 1993 Energy Research Corporation (ERC) estimates.

(i) The estimated average cost per kilowatt and qualitative risk were compared for all five proposed power systems: Baseline, PEM, MC, PA and SO. They were numerically ranked from the most preferred to the least preferred based on the combination of measured cost and qualitative risk.

(6) Destroyer and Corvette Variant designs were received from CDNSWC 214 and BLA, respectively. These Variant designs, or "altered Baselines", have specified Baseline systems replaced with PEM fuel cell systems.

(7) Variant ship costs were estimated in a similar manner as those which were estimated for each Baseline. However, each Variant includes the cost of those PEM fuel cell and PEM fuel cell-related systems which replace specified Baseline systems.

(8) Some degree of technology impact occurs when incorporating fuel cell systems into each Baseline. These technology impacts typically parallel cost impacts. Cost impacts were measured by comparing Variant costs to respective Baseline costs from the following four perspectives:

(a) Propulsion Plant (SWBS 200)
(b) Electric Plant (SWBS 300)
(c) Balance of Ship, i.e. BCC - ($Cost_{200}$ + $Cost_{300}$)
(d) Total BCC

These comparisons highlighted any significant acquisition cost drivers, or cost savings, which result from substituting Baseline systems with PEM fuel cell systems.

B. Acquisition, O&S, LCC, and NPV Cost:

(1) The Acquisition Costs, for the Baselines and Variants, exclude all estimates for GFE and combat systems. The cost model which estimates Acquisition Cost, simply applies percentages of the BCC to all Acquisition Cost categories except "Plans". An algorithm was developed by CDNSWC 211 which estimates the cost associated with "Plans" to develop a T1 ship. The breakout of Acquisition Cost is described in detail in Appendix F and Table F.6.

(2) O&S costs for the Baselines were calculated as described in Appendix F. Variant O&S added those costs associated with maintaining and replacing fuel cell equipment during the thirty-year ship life. Current industry guidelines suggest the following fuel cell system maintenance routine:

a. Fuel cell stacks are replaced at 5 year intervals (5 change-outs)
b. Desulfurizer units are replaced once per year (29 change-outs)
c. Sulfur removal is 5% of fuel costs

Alternative fuel cell stack replacement scenarios of zero, one and two change-outs were investigated to see the cost impacts on O&S and LCC.

At present, fuel cell system operating labor and maintenance costs are assumed to be the same as the Baseline power systems.

Annual fuel consumption rates were provided for all Baselines and Variants, assumed to have typical mission profiles. Fuel cost was calculated by multiplying the consumption rate (barrels of fuel per year) by the current cost for Navy diesel fuel (cost per barrel):

a. Destroyer Annual Mission Profile = 2700 hours underway; 1500 hours anchor

b. Corvette Annual Mission Profile = 2656 hours underway, 144 hours anchor

(3) The LCC and NPV for all ships were calculated as described in Appendix F. Although LCC includes costs for RDT&E, GFE items, combat systems, and disposal costs, these were not included in this study. The LCCs, for this study, are an accumulation of Acquisition and O&S costs over a thirty year ship life. LCC is converted to a NPV using a discount rate of 4.5%. The NPVs of all Variants were compared to their respective baselines to measure the cost feasibility of PEM fuel cell technology from a LCC perspective.